①

DTIC
ELECTE
JUN 2 7 1991
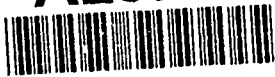S   D
C

An Exploration of Integrated Ground Weapons Concepts for Armor/Anti-Armor Missions

Randall Steeb, Keith Brendley, Dan Norton, John Bondanella,
Richard Salter, Terrell G. Covington

91-03377

‖‖‖‖‖‖‖‖‖‖‖‖‖‖‖‖‖‖‖

91 6 25 008

RAND | NATIONAL DEFENSE
RESEARCH INSTITUTE

R-3837-DARPA

An Exploration of Integrated Ground Weapons Concepts for Armor/Anti-Armor Missions

Randall Steeb, Keith Brendley, Dan Norton, John Bondanella, Richard Salter, Terrell G. Covington

Prepared for the
Defense Advanced Research Projects Agency

RAND

PREFACE

This report, conducted for the Tactical Technology Office, Defense Advanced Research Projects Agency (DARPA), summarizes the results of an analytic exploration of future armored vehicle designs. The work was carried out in the Applied Science and Technology Program of the National Defense Research Institute, RAND's federally funded research and development center sponsored by the Office of the Secretary of Defense and the Joint Chiefs of Staff.

The work focuses on the design of light and heavy antiarmor vehicles. Surveys and analyses are made of protection systems, weapon systems, mobility systems, sensor packages, crewspace designs, and electronics architectures. Many of the recommended configurations were tested using in-house computer simulations. The report should be of interest to researchers in ground vehicle design, technology assessment, and tactical simulation.

SUMMARY

Armored warfare has become a spiraling escalation of weapons and protection systems. Both sides continually work to field systems with more firepower, more effective armor, better sensors, smaller signatures, and better command and control. Even in the budget-conscious post-CFE (conventional armed forces in Europe) environment, these trends should continue. In this report, we explore some evolutionary and revolutionary approaches to armor/antiarmor design, concentrating on reduced (two- and three-man) crews. We assess the utility of many of the designs using simulations such as JANUS, RAVUM, and RISE.

In the process of developing system designs, we surveyed many constituent technologies. We studied protection systems using a vulnerability model. We examined solid propellent, liquid propellent, and electromagnetic gun systems, and we reviewed antiarmor missile systems having different means of control and kill mechanisms. We considered turbine, diesel, and rotary engine propulsion systems, with both conventional and electric transmissions. Finally, we analyzed electronics systems such as sensor suites, display/control configurations, communication systems, signal processors, and environmental control packages. For most of these technologies, we made recommendations for the near term, five to 10 years, and the far term, 10 to 20 years. We integrated many of the near-term recommendations into our preliminary designs for light and heavy vehicles.

For future main battle tank (MBT) designs, we found that armoring the crew compartment against a conservatively projected Soviet threat is extremely difficult. Even our smallest, two-man design with an external gun is estimated to weigh 55 tons. Three-man designs, especially those with one or more crew members having all-around top viewing, are substantially heavier. In all cases, we found that placement of the crew at the front, gun and autoloader in the center, and engine at the rear was the most efficient configuration, optimizing the frontal, flank, and top attack protection for the crew, electronics, and ammunition. It also reduces problems with firing torques, engine thermal signature, and hatch placement compared with other configurations.

Our investigation of electromagnetic (EM) guns showed that the technology is not sufficiently mature for the time frame considered (five to 10 years). There are major problems in energy generation, storage. and conversion processes. We estimated that even with optimistic technology projections, placing a 60-MJ EM gun in a future two-man vehicle with sufficient armor to meet the projected threat results in an MBT weighing over 90 tons. The frontal silhouette would have an area almost twice that of the current M1-A1 tank.

For our MBT system studies, we concentrated on use of a conventional solid propellent gun with something over twice the kinetic energy of the current 120-mm gun. A carousel autoloader was posited with capacity for 35 two-piece rounds. In the far term, we recommend exploration of liquid propellent and combustion-augmented electro-thermal guns, which have advantages in growth potential, system integration, and vehicle survivability over solid propellent (SP) guns.

In comparing two- and three-man MBT designs, we noted that some battlefield functions are best carried out by three-man crews, such as firing on the move with both the main gun and secondary armaments, and target engagement while communicating tactical data.

Other places where three crew members would be beneficial are in emergency responses, maintenance functions, and round-the-clock operations without crew replacement. The main advantage of a two-man crew is a smaller, lighter, and less vulnerable vehicle.

Our sensor designs assume the crew operates primarily in a buttoned-up mode on the battlefield. Two independent armored sensor pods rest on telescoping stalks rising from the turret. Each pod has a forward-looking infrared (FLIR) sensor, day TV, and laser rangefinder. A turret-mounted millimeter-wave radar is optional, primarily for use in bi-spectral smoke conditions. Chassis-mounted low-light-level TV sensors provide redundancy. All sensors feed video signals through a fiber optic network to cathode ray tube (CRT) displays in the crewspace. For the far term, we expect that at least one helmet-mounted display will be employed, providing panoramic viewing and integrated target designation.

Use of reduced crews on vehicles will require substantial aiding through automation and artificial intelligence. We specify eight aiding modules in our designs: (1) target acquisition and engagement, (2) command and control, (3) situation report and assessment, (4) navigation, (5) system control (man-machine interface), (6) security status, (7) maintenance and supply status, and (8) power distribution and conditioning. These modules relieve the operators of many time-consuming functions, yet are always subject to operator override. Automatic target recognition should also be present, although only in a target cueing mode in the near term. The entire electronics package—processors, mass storage, graphics drivers, communication systems, power bus, and data network—should fit in the sponson areas next to the crew.

We developed four designs for a near-term MBT. All have large (~140-mm) solid propellent guns, carousel autoloaders, and telescopic sensor masts. All use 95th percentile crew members, and to the degree possible, all achieve the same armor protection levels and have the same propulsion, suspension, and electronics. The first of the four configurations is a remote gun design with two men in the hull. This is something of a baseline, since it is the smallest and lightest (55 tons) of the designs. For comparison, the current M1-A1 weighs some 63–66 tons, is 41 in. longer, and has a turret cross-section area roughly twice as large from the front and 60 percent larger from the side. The second MBT design expands this to include three men in the hull, with the crew staggered (three abreast does not allow sufficient side armor for the crew compartment). This vehicle adds 30 in. in length and 5.5 tons to the two-man system, but has advantages in crew tasking and habitability. The third design places two men in the hull and one behind the turret, still with a remote gun. This design gives the commander good overall viewing and orientation with the gun, but results in special vulnerabilities and major weight penalties (74.5 ton estimate). The fourth design is a more conventional manned turret design, with a driver in the hull and two crewmen in the turret. It is somewhat comparable to the new French LeClerc, but with a larger gun and more armor. The problems are a massive turret and increased crew vulnerability. The estimated weight is 74 tons.

We also explored options for light vehicle antiarmor designs (15–30 tons). The designs were all hypervelocity missile (HVM) carrying variants of the Bradley armored fighting vehicle and the wheeled LAV (Marine Corps light armored vehicle). The designs did not alter the armor, propulsion, or suspension systems of the current vehicles, but they substituted a HVM launcher and ammunition compartment for the gun turret. They also replaced the current displays and controls with advanced crew stations equivalent to those in the MBT de-

signs. We examined the potential of these light armor designs closely, but did not compare them with the MBT designs.

The main problem in development of an HVM Bradley is finding room for a sufficient number of the large (10 ft long) kinetic energy missiles (KEMs). We arrived at a space-efficient design for elevation and rotation of four missiles at a time, from a 28 missile bay in the two-man HVM Bradley. A similar three-man design reduced this to 20 missiles. No major advantage was seen for changing to the larger (25 in. longer) stretched Bradley chassis now used in the multiple-launch rocket system (MLRS). Only one telescopic sensor mast will be present, because the KEM missile module has its own search and targeting sensor suite. The length and width of the HVM Bradley is identical to that of the current Bradley; the height drops some 14 in. The weight increases from 25 tons to 30.8 tons. A major problem with the HVM Bradley will be vulnerability of the highly explosive missiles in the lightly protected vehicle.

Incorporating the HVM missile package in the smaller LAV is somewhat more difficult. We again produced designs for two- and three-man versions, but found that a three-man crew is extremely cramped. The two-man version was able to carry 24 missiles. As with the Bradley designs, the missiles are vulnerable in the lightly protected vehicle. The weight of the two-man version is estimated to increase 4 tons from the current version, from 13.6 to 17.7 tons.

JANUS simulation runs were performed using the two-man MBT and HVM Bradley concepts. JANUS is an interactive, battalion-level, two-sided wargame with resolution down to individual vehicles. The units move and fight over a computer-generated Defense Mapping Agency (DMA) terrain map, with calculation of line-of-sight and sensor contacts. Five tactical vignettes were run, all taken from the same front concept of operation in central Europe. The vignettes were (1) Blue defense short range (4:1 Red to Blue force ratio, detection ranges generally 800–1200 meters), (2) Blue defense long range (same force ratio, detection ranges generally beyond 2000 meters), (3) Blue counterattack short range, (4) Blue counterattack long range, and (5) meeting engagement (matched forces, short range).

The JANUS runs pitted current and advanced (two-man) Blue MBTs against current and advanced Red MBTs. All simulation results were unclassified. We also augmented the forces incrementally in the short-range defense and counterattack scenarios with armored personnel carriers (APCs), artillery, mines, helicopters, and bispectral smoke.

Reduced crew vehicle (RCV) superiority in armor and weapon performance was evident in both the defensive and offensive scenarios, with loss exchange ratios three to 15 times that of the current Blue MBT. Only in scenarios with heavy use of bispectral smoke did the RCV performance reduce to that of the M1-A1 or the Red MBTs. Millimeter wave radar, which may have alleviated some of this effect, was not modeled in the simulation. Addition of HVM Bradleys to the force in the Blue defense short-range scenario did not affect the outcomes significantly.

We also examined the difficulty of implementing many of the aiding modules, through use of the RISE (RAND Integrated Simulation Environment) system. RISE is an object-oriented Lisp-based system with DMA terrain representation. We coded rudimentary programs for the situation assessment, command and control, and target engagement modules. We ran them in several exemplary scenarios and arrived at data points for estimating memory and processing requirements. Target acquisition and engagement functions were seen to be the

most complex, particularly if projection-based planning is included (where each option is simulated into the future for evaluation). For the near term, we estimate that 6–8 MIPS of processing power and 10–15 Mbytes of memory should be sufficient. Our exploratory work was done in Lisp, but similar load levels are expected if the system is coded in C or ADA language.

In sum, we found that reduced crew antiarmor vehicle concepts should be achievable using available technology. The designs are projected to be smaller, more maneuverable, more lethal, and less vulnerable than their currently fielded counterparts. Tank-killing capabilities should be feasible with vehicles as small and light as the LAV. Sufficient armor protection to conduct offensive operations against next-generation Soviet MBTs, however, requires an MBT platform.

A substantial amount of research remains to be done before these concepts can be validated and turned into detailed design specifications. In-depth analyses and simulations need to be run on armor penetration, vehicle dynamics, and vehicle electronics. In particular, high-fidelity simulation using SIMNET and other systems should be used to check crew interactions and system operational effectiveness. We will also need to determine system effectiveness in the light of post-CFE scenarios, in which nonlinear battlefields and fast deployment will be emphasized. MBTs may be relegated to a lesser role than in current warfare, even in offensive operations. In sum, simulation and field tests will be needed to refine and test the designs, using a variety of missions, force mixes, and terrain and weather conditions.

ACKNOWLEDGMENTS

CONTENTS

FIGURES

TABLES

GLOSSARY

AI	Artificial intelligence
AIPS	Advanced integrated propulsion system
APC	Armored personnel carrier
APU	Auxiliary power unit
ADA	A structured programming language to be used in many future military systems
ATGM	Antitank guided missile
ATR	Automatic target recognition
BMP	Soviet armored personnel carrier
BOPS	Billions of operations per second
C	A common structured programming language
CE	Chemical energy (a type of round or missile)
CITV	Commander's independent thermal viewer
CRT	Cathode ray tube
DMA	Defense Mapping Agency
ED	Electric drive
EM gun	Electromagnetic gun (or railgun)
ET gun	Electrothermal gun
FASCAM	Family of scatterable mines
FLIR	Forward looking infrared sensor
FPA	Focal plane array
HEAT	High explosive, antitank
HMD	Helmet-mounted display
HUD	Head-up display
HVM	Hypervelocity missile
ICM	Improved conventional munitions (artillery)
IFF	Identification, friend or foe
JANUS	A two-sided battalion/brigade-level simulation system
JTIDS	Joint tactical information distribution system
KE	Kinetic energy
KEM	Kinetic energy missile (also known as HVM)
LAV	Marine Corps light armored vehicle
Lisp	List processing language, a common AI language
LLLTV	Low-light-level television
LOS	Line of sight
LP	Liquid propellent
MBT	Main battle tank
Mbytes	Millions of bytes of memory
MIPS	Millions of instructions per second
MJ	Megajoule (energy unit)
MLRS	Multiple-launch rocket system

MTI	Moving target indication
MMW	Millimeter wave
NBC	Nuclear, biological, chemical
POSNAV	An automated position/navigation system
RAVUM	A vehicle vulnerability model
RCV	Reduced crew vehicle
RHA	Rolled homogeneous (steel) armor
RISE	RAND Integrated Simulation Environment
RPV	Remotely piloted vehicle
SCORE	Stratified charge omnivorous rotary engine
SDI	Strategic Defense Initiative
SIMNET	A distributed, interactive battalion-level simulation system
SP	Solid propellent
TACOM	Tank-Automotive Command
TMEPS	Transverse-mounted engine propulsion system
TTS	Tank thermal sight
VIC	Vector in Commander

I. BACKGROUND AND MOTIVATION

Armored vehicles are the roughly hewn product of a constant struggle between more powerful weapons and better protection. For example, the M1-A1 tank, with its composite armor and low profile, was barely on the scene before the Soviets upgraded their tanks and introduced new fire-control systems. The introduction of the 120-mm smoothbore into NATO armies seems to have coincided with the development of the heavily armored Soviet T-80 tank. The U.S. Army recently began countering the burgeoning Soviet threat with use of extremely dense, depleted uranium armor in critical areas of the M1. With the advent of reactive and special armors, antitank guided missiles have become less effective at attacking the frontal arc and flanks of main battle tanks (MBTs), but new control techniques now facilitate top attacks. In short, both sides continually introduce new technology and briefly hold some edge in firepower, protection, mobility, or automation. As technological breakthroughs accelerate, both sides will find it important to introduce new systems at a faster pace.

In this report, we examine some near- and far-term options for dramatically enhancing the effectiveness of U.S. armored vehicles. We are concentrating on dramatic change rather than conservative, evolutionary processes, because of the long U.S. procurement cycle. The technological options we are considering include new weapons systems, autoloaders, automatic target recognition systems, propulsion packages, sensor suites, and even completely new chassis configurations. All of our options rely heavily on automation to reduce the crew burden.

Some of the impetus for our work comes from upgrade programs on the M1-A1, Bradley, and U.S. Marine Corps light armored vehicle (LAV). These efforts indicate that adding sufficient armor to counter new gun developments will result in extraordinarily massive vehicles. At the same time, weapons and fire control systems on current vehicles are undergoing frequent improvement cycles. This has prompted those working on the joint Defense Advanced Research Projects Agency/Army/Marine Corps Armor/Antiarmor initiative to explore revolutionary approaches. Our role in the program is to evaluate new technologies, integrate promising candidates, and recommend system configurations for light and heavy vehicles.

The time frame we are working in spans some 5 to 20 years into the future. The rapidly changing post-CFE (conventional armed forces in Europe) environment may push the United States to move to a mix of lighter, more deployable and sustainable systems than the current forward-deployed heavy force. While MBTs may be reduced, the force projection capability will still require development of direct-fire systems able to engage the projected Soviet threat. We have concentrated on vehicles with onboard crews, typically two or three men. However, much of the technology also applies to robotic or supervisory control systems. Virtually all aspects of situation assessment, planning, and coordination onboard the vehicles will be automated to some extent.

The principal output of our work is a set of candidate designs for MBTs and light armored vehicles, developed through analytic studies, simulations, and computer-aided design exercises. The organization of the report roughly follows our sequence of development. Section II gives a short historical perspective on armored vehicle evolution. Section III is a

survey of applicable technologies, with recommendations for near- and far-term systems. Section IV presents recommended MBT configurations, including two- and three-man versions with remote and manned turrets. Section V describes some light armored vehicle designs, including two- and three-man missile-carrying Bradley fighting vehicles and LAVs. Section VI gives an overview of our simulation work, which involves extensive use of the JANUS and RISE simulation environments. Section VII summarizes our findings and suggests further work. The appendixes, finally, give details of the simulation work and recommended onboard automation systems.

II. HISTORICAL PERSPECTIVE

Ever since they appeared almost three-quarters of a century ago, tanks have played a major role in ground warfare. They have succeeded at this because they embody a unique combination of firepower, mobility, and protection. They are mobile, protected, direct-fire weapon systems for which no effective alternatives or substitutes have been found. As a result, tanks have not only survived, but retained their importance in the face of a succession of threats over the years, from antitank artillery and infantry antitank weapons, through rocket-firing aircraft, to attack helicopters and antitank guided missiles.

To maintain their effectiveness, tanks have had to adapt to the changing battlefield environment. The original World War I British tanks were slow and cumbersome, with long tracks designed for crossing wide enemy trenches. With time, the assault roles extended to more mobile operations, and tanks became more maneuverable and compact. They also acquired rotating turrets, and by the end of World War II, most had five-man crews in place of the six to eight in the early tanks.

The primary requirement for battlefield effectiveness was armament capable of defeating a wide range of targets. The most difficult targets were other tanks, and when tanks lacked guns capable of defeating their opponents, they suffered heavily. Vivid examples were the losses suffered in World War II by the inadequately armed British and U.S. tanks when faced with German Panther and Tiger tanks. The cardinal importance of tank armament has been generally recognized since then, with tanks armed with progressively more powerful guns. The caliber of tank guns has risen during the past 40 years from 85 or 90 mm, through 100 and 105 mm, to 120 and 125 mm on the current generation of Western and Soviet tanks.

The increase in armament has been accompanied by progressive increases in armor protection. At first, tanks had armor only 14-mm (or even 6-mm) thick, but by the end of World War II, thickness had risen to as much as 150 mm. Since then, many tanks have had frontal armor over 250-mm thick, but some, such as the French AMX-30 and the German Leopard I, have had armor no thicker than 50 or 70 mm.

A reason for some tanks having significantly less armor than others was the widespread belief that the survivability of tanks was more likely to be improved by increasing their mobility and agility than by adding to their armor protection. This belief manifested itself in demands to keep the weight low and the power-to-weight ratio high (to 30 hp per ton or more). The extreme of this line of development was reached during the mid-1970s with the construction in Germany of the experimental VT-1 turretless tanks with twin 105- or 120-mm guns and very high power-to-weight ratios. The vehicles were expected to avoid being hit by executing violent evasive maneuvers, but their ability to do so proved to be severely restricted by terrain. Moreover, a law of diminishing returns with respect to mobility and agility set in even below 30 hp per ton.

On the other hand, the experience of the Arab-Israeli wars of 1967 and 1973 proved that heavy armor did significantly increase survivability. Survivability was further increased by the development of special armors. Prior to the introduction of special armors, the maximum level of frontal armor was exemplified by the British Chieftain tank, which had the equiva-

3

lent of 390 mm of rolled homogeneous steel armor (RHA). With special armors, frontal protection rose to the equivalent of 600 mm of RHA against shaped charge weapons. The level of protection increased still further with the addition of explosively reactive armor, first used by Israeli tanks in 1982 and now widely employed by Soviet tanks.

Further increases in armor protection are constrained by weight and space limitations. However, protection can be increased if the volume of tanks is reduced. This is possible because armor weight is proportional to the volume it envelops, so that a more compact tank can have more armor for a given weight.

A major factor governing the internal volume of tanks is the space occupied by their crews. On the average, each crewman needs at least 1.3 m^3 of space. Because of this, there has been a trend to reduce the number of crewmen. Some tanks built during the 1950s, such as the U.S. M-47, still had crews of five men, as did most tanks in World War II. Almost all battle tanks built since then, however, have had a crew of four—a driver in the hull and a commander, gunner, and loader in the turret.

There was some opposition from the users to the elimination of the fifth crewman, who was located in the hull alongside the driver and generally operated a machine gun. Arguments for his retention were not based on his effectiveness as a gunner, but on the grounds that he was needed to help maintain the tank and to perform various tasks outside it, such as sentry duties. Whatever his usefulness, it was outweighed by the space he occupied and the adverse impact on the tank's internal volume and weight. The fifth man was soon dispensed with and four-man crews were deemed adequate.

Even smaller crews, of only three men, have been widely accepted for light tanks and armored cars since before World War II, largely because these vehicles use much lighter armament than battle tanks. The lighter armament is easier to service, so that commanders and gunners can double in the role of loaders. However, this ceased to be valid when light tanks and armored cars began to be armed with guns of up to 90 mm. A more convincing explanation for use of three-man crews is that the light vehicles are not expected to engage in sustained combat. Thus their main armament does not have to be loaded as frequently or resupplied as rapidly as that of battle tanks, reducing the need for a loader. Also, light tanks and armored cars are usually employed in mixed units, particularly of cavalry or reconnaissance units, ensuring the availability of men to take care of maintenance, local security, and other duties normally performed by crews in "pure" tank units.

Apart from the organizational aspects, any attempt to reduce the battle tank crew to three men depends critically on the development of an effective automatic loading system. The first successful use of a three-man tank with heavy armament is represented by the French AMX-13, which was introduced in 1950 and had a semi-automatic loading system for its 75- and then 105-mm gun. The AMX-13 was originally produced as a tank destroyer, but it was used as a tank by the Israeli army in the Suez operations of 1956 and the Six-day War of 1967. It is still used by the armies of Singapore and Ecuador, and its turret, with its bustle semi-automatic loader, is also mounted on vehicles used by the armies of Austria, Morocco, Tunisia, Bolivia, and Argentina. In spite of its widespread use, this tank has very light armor and a cramped turret, and it has been confined to limited roles.

The first battle tank to be put into service with a three-man crew was the Swedish S-tank, introduced in the late 1960s. The S-tank has a turretless configuration, with the gun mounting fixed in the hull and a fully automatic loading system. This made integrated

driving and gun controls possible, so that it could be fully operated by one man, although it was conceived as a two-man tank. At the request of the Swedish army, it was redesigned to accommodate a three-man crew. The third crew station was intended primarily to provide room for platoon or company commanders, but the crewmen occupying it also act as drivers in reverse and radio operators. The S-tank has been operated successfully by the Swedish army for 20 years, and British tests have shown that it can be operated efficiently by its three-man crew for 96 hours of continuous battlefield activity.

Since 1970, the Soviet army also introduced into service a series of three-man tanks with a more conventional turreted configuration, starting with the T-64 and T-72. The commonly accepted explanation for Soviet adoption of three-man crews and autoloaders is that it has allowed a significant size reduction. Also, it is thought that the somewhat limited or narrowly defined battlefield tasks of Soviet tanks have encouraged use of three-man crews. Whatever the reason, the Soviet army has deployed three-man tanks on an increasing scale. Export versions of the T-72 have been accepted by the armies of several Arab countries and by Yugoslavia, Finland, and India, without appearing to have created problems for any of them.

U.S. interest in battle tanks with three-man crews was first directed on configurations with all three men, including the driver, located in the turret. This led in the mid-1960s to the design of the MBT-70, with three men in the turret and a bustle autoloader. However, the location of the driver in the turret led to orientation problems as well as complexity associated with the counterrotating capsule in which the driver was located. No other attempt to develop a three-man tank was made until the construction of the Tank Test Bed (based on the M1 tank chassis) in the mid-1980s. This had a novel configuration with all three crewmen located in the front of the hull and a remotely operated, unmanned 120-mm gun turret.

West German and Swiss armies also sponsored development of three-man battle tank designs during the 1970s, but found that they did not offer sufficient advantage at the time over the Leopard II with its conventional configuration and four-man crew. To enable them to reduce the crew to three men, both the German and Swiss designs incorporated bustle- or hull-mounted autoloaders.

On the other hand, three-man tanks were adopted in the early 1980s by the French and Japanese armies, in the shape of the AMX LeClerc and the TK-X. Both tanks are still at the prototype stage. They each have the driver in the hull, the commander and gunner in the turret, and loading performed by a bustle autoloader. However, the trend to three-man crews has not yet become general. Several tanks developed during the 1980s still have the conventional configuration and four-man crews. These include the British Challenger, South Korean Type 88, the Brazilian EE-T1 Osorio, the Italian C-1 Ariete, and the Israeli Merkava Mark 3. Moreover, highly experienced tank designers like General Tal, who has directed the evolution of the Merkava from its inception, consider four-man crews essential to prolonged combat.

None of the battle tanks currently under development has a remotely operated gun and a crew located in the hull. where crew members would be best protected. The main obstacle to this appears to have been the difficulty of providing satisfactory indirect or remote viewing. In particular, the available optronic sensors have had problems with field-of-view limitations, resolution, operator orientation, reliability, and cost. Many of these problems are now being overcome, however, and the dangers of traditional, out-of-hatch viewing are

increasing. These and other considerations are brought out in detail in the following section on Technology and Concepts, and lead directly to our design recommendations in Sec. IV.

III. TECHNOLOGY AND CONCEPTS

INTRODUCTION

This section discusses the technology needed for effective future ground weapon systems. Recommendations are made for all aspects of light and heavy armored vehicle design: protection, weapons, suspension, propulsion, sensors, communications, crewspace, and special electronics. Each subsection discusses requirements for the technology area, presents options, makes comparisons and projections, and gives recommendations.

There are many interactions between components. Fire control, for example, requires integration of sensors, communication, displays/controls, and weapons. Firing on the move adds suspension and propulsion to the equation. Even simple navigation requires coordination between sensing, communication, processing, and control/display systems. Many of these interactions will be noted in the individual subsections.

The specifications in this report are all derived from unclassified sources. The resulting vehicle designs should therefore be considered generic in nature.

This technology section lays the groundwork for the detailed reduced crew vehicle (RCV) designs presented in Secs. IV and V. The section broadly surveys technologies applicable to main battle tank (MBT) and light armored vehicles. General recommendations are made and later put into place when specific configurations are presented. When possible, the options have been divided into near-term (five to 10 years) and far-term applications (10 to 20 years).

PROTECTION SYSTEMS

This subsection describes the requirements and technologies for armoring future ground combat vehicles. We restrict ourselves to MBT analyses because our other designs are based on the Bradley fighting vehicle and the LAV chassis.

The protection system for a reduced crew vehicle can be defined by a number of constraints and variables. These values stem from the threat facing the RCV, protection technology, protection priorities, and practical design considerations. This subsection will define the protection system for the RCV and develop a general methodology for calculating the optimal protection system for an MBT.

A defining characteristic of the MBT is that armor protects certain areas from the most lethal threats on the battlefield. Of course, design considerations other than armor thickness influence the survivability of the vehicle. A broader definition of protection systems is to:

- Avoid detection
- If detected, avoid acquisition
- If acquired, avoid being hit
- If hit, avoid penetration
- If penetrated, avoid damage

The main focus here will be on avoiding penetration if hit. The other protection variables become apparent when viewing an actual design, and will be discussed at greater length in the configuration section.

The Threat: A Parametric Definition

In the United States, the march from the drafting table to the shop floor is measured in years rather than miles, and if predicting the current threat is an uncertain endeavor, how much more so predicting the threat ten or twenty years hence must be. One should not rely upon such predictions unless necessary, as it certainly will be at some point in the design process. However, in the early stages of design, it is preferable to describe the broad qualitative aspects of the threat within a bounded range of parameters. Such a methodology allows for a better understanding of the protection concept—its robustness and durability over a range of threats.

In the past, the threat has been defined in terms of its likely penetration depth into rolled homogeneous armor (RHA). Armors other than RHA may then be characterized by comparing the masses of this new armor and of RHA required to defeat some threat. An advanced armor that requires only half the mass of RHA to defeat a certain munition is said to be twice as mass efficient as RHA. However, this method of definition has proven unsatisfactory in the latter design stages because of the wide variety of armors and antiarmor munitions in modern inventories. For example, an advanced armor may be conceived that would be lighter than RHA to counter one threat but heavier to counter another. What is the mass efficiency of the advanced armor then? Obviously, for a specific armor, there is no such thing as a general mass efficiency, and one must speak of specific armors versus specific threats.

Lack of a general measure presents a dilemma when neither the threat nor the armor is known. However, the ambiguity that seemingly poses a difficulty also resolves it. Either threat or armor defined in terms of a general efficiency is acceptable when neither the actual threat or armor is defined. Care must be taken to ensure that the range of threats and armor efficiencies is sufficiently broad to account for actual threat/armor combinations one may encounter in the later design stages.

One example outlining the acceptability of a general efficiency parameter for the early design stage is as follows. There are two postulated threats, T1 and T2, and the designer has two armors, A1 and A2, at his disposal to defeat those threats. It is suspected that armor A1 requires a mass M to protect a given area against threat T1, but requires 3M to defeat T2. Conversely, A2 defeats both T1 and T2 with a mass of 2M. The designer is faced with a difficult choice. Armor A2 would be the more conservative decision, but if threat T2 never materializes, then the army that fielded armor A1 has an advantage. In any case, the actual threat/armor combination is critical to the decision and may not be described by general parameters.

However, earlier in the design process, before the actual armor decision must be made, a range of threats may be described in terms of RHA equivalents. Armors may then be couched in terms of mass efficiencies such that actual armor/threat combinations would be contained within that range. If armor A2 above were RHA, then the mass efficiencies for the above armors would range from 0.5 to 2. Therefore, for the early design phase, real armors of

interest would be contained within that mass efficiency range, and a study that used that range may prove of some utility in later design stages.

In this study, the two basic classes of variables—the threat and armor technology—are simplistically defined so that a large number of threat and technology combinations may be more easily examined. Threats are defined in terms of RHA equivalent penetrations, and armors are defined in terms of mass efficiencies. Six basic types of threat are defined: a large kinetic energy (KE) threat, a large chemical energy (CE) threat, a lesser KE threat (ke), a lesser CE threat (ce), a top threat, and a bottom threat. The threats were often defined in terms of the large KE threat as shown below. However, this method was not always used and was discarded completely when actual designs were considered.

$$KE = given$$
$$CE = 2 \times KE$$
$$ke = KE/10$$
$$ce = KE/2$$

Armor technologies are defined in terms of mass efficiency (E_m) and space efficiency (E_s) for each of the classes of threat. Mass and space efficiency are defined in terms of RHA:

$$E_m = \frac{\text{Mass of RHA required to defeat threat}}{\text{Mass of armor required to defeat threat}}$$

$$E_s = \frac{\text{Line of sight penetration distance for RHA to defeat threat}}{\text{Line of sight penetration distance for armor to defeat threat}}$$

The mass efficiency range used in this study is shown in Table 1.

Note that the postulated armors are projected to be much more effective in defeating CE warheads than KE penetrators. The advent of reactive armors has given rise to this large discrepancy. The mass efficiencies presented here are used in a different manner than they are normally. Mass efficiencies usually relate to the mass efficiency of the entire armor versus the threat. In this study, it was assumed that the technologies for KE and CE armors are advancing at sufficiently different rates to justify designating KE and CE efficiencies separately. This method of defining armor technology allows greater flexibility in defining threat/armor combinations. For example, KE and CE technology levels may be independently varied, as may KE and CE threat levels.

This method allows the armor suite to be optimized for the given threat. Conversely, if one were to define an armor in terms of a combined mass efficiency, the required mass of armor would be driven by the combination of most severe threat and lowest mass efficiency. Certain combinations of KE mass efficiencies ($E_{m,KE}$) and CE mass efficiencies ($E_{m,CE}$) could yield confusing results when the threat is varied. For example, an armor with $E_{m,KE} = 1$ and $E_{m,CE} = 3$ would be optimal for defeating a CE threat that is three times as severe as the KE threat. However, if the CE threat were less than this, then the armor would be overdesigned for CE. Therefore, as the CE threat increased, the armor mass would remain constant until a three-to-one ratio between the threats was reached. For a parametric study such as this one, such behavior tends to cloud the results.

Table 1

MASS EFFICIENCIES OF ARMOR
TECHNOLOGY VARIATIONS

Threat	Mass Efficiency		
	Low	Medium	High
KE	1.5	2	3
CE	7	10	15

The KE armor may be thought of as the base or structural armor and the CE armor as an applique, although that particular sort of configuration is not required for this method of defining mass efficiencies. The KE and CE armors, while most efficient at defeating their particular type of threat, also contribute to defeating the other threat type.

An example of how the two armors may be combined follows. Suppose that the KE threat (P_{KE}) is 500-mm RHA and the CE threat is $2 \times P_{KE}$. We wish to combine two armors to defeat these two threats with minimal mass. The first armor plate, plate 1, is optimized against KE, and the second plate, plate 2, is optimized against CE. We wish to use a KE armor with $E_{m,KE,1} = 2$ and a CE armor with $E_{m,CE,2} = 10$, where the numerical subscripts refer to plate 1 or plate 2. The KE and CE armors are also somewhat effective against each other's threats. In this example, we assume the mass efficiency of the KE armor versus the CE threat is equivalent to its efficiency in defeating the KE threat, $E_{m,CE,1} = 2$, and the mass efficiency of the CE armor versus the KE threat is one, $E_{m,KE,2} = 1$. We wish to find the minimal areal density (AD) to defeat both threats. To do so, we first find the RHA equivalent thickness of the KE armor plate, L_{KE}, and the CE armor plate, L_{CE}. The optimization statement may be posed as follows:

$$P_{KE} \leq L_{KE} \times E_{m,KE,1} + L_{CE} \times E_{m,KE,2} \tag{1}$$

$$P_{CE} \leq L_{KE} \times E_{m,CE,1} + L_{CE} \times E_{m,CE,2} \tag{2}$$

$$AD = r_{RHA} \times (L_{KE} + L_{CE}) \tag{3}$$

In most practical cases, the above set of equations may be uniquely solved for AD. In this example, the areal density is 2194 kg/m^2, compared with an areal density of 7800 kg/m^2 for RHA to defeat the same threats. This implies a combined mass efficiency of 3.6.

Penetration is only one aspect of the threat; another equally important aspect is the section of the target that a given threat is likely to strike. To a large extent, this is a function of the threat platform and weapon. A notional tabulation of platforms and weapons is shown in Table 2. Here, threats are categorized by the thickness of armor they are designed to penetrate and the portion of the target they are designed to attack.

For example, the dispensed medium KE munition in the table could be an explosively formed projectile (EFP) dispensed from a cruise missile or tactical missile. As time goes on, the most severe threat will expand to azimuths away from the frontal arc normally associated with armored vehicles. However, in the near term, the heaviest threat will remain concentrated toward the front of the vehicle. Heavy threats are defined here as those capable of

Table 2

NOTIONAL CHARACTERISTICS OF THREAT SYSTEMS

Threat	Munition					
	Heavy KE	Heavy CE	Medium KE	Medium CE	Light KE	Light CE
MBT	Front			Front		
Helicopter		Front, side	Side			
APC		Front				
Troops					Side	Side
Artillery			Top	Top	Top	
Dispensed			Top			
Fixed wing			Top			
Mines			Side, bottom			

penetrating the most armor; tank-fired sabot rounds and helicopter-launched antitank guided missiles (ATGMs) are good examples. Light threats are less capable of penetrating armor but are generally more numerous on the battlefield. Hand-held ATGMs and smaller-caliber armor piercing rounds are light threat examples. Medium threats fall between these two categories, for example, a tank-fired, high-explosive, antitank (HEAT) round.

The severity of top threat is a function of the elevation angle at which it may be expected to attack. In general, as the angle approaches the vertical, the penetration capability of the attacking weapons and the armor thickness both decrease, although more effective top-attack munitions are now in development. From Fig. 1 and Table 2, one may conclude that, once they are fielded, dispensed munitions will pose the more difficult top threat.

The tank will not always be frontally attacked by heavy threats; a certain percentage of shots will emanate from the tank side and rear. Shot distribution around the tank has often been studied. One of the largest studies used WW II data and predicted that the shot distribution will resemble a cardioid, as shown in Fig. 2. The angles in Fig. 2 are measured from the front of the tank, sweeping toward the rear. From the figure, one can see that the likelihood of striking the front of the vehicle is far greater than striking the rear. Other shot distributions have been used. For example, German researchers tend to model the shot distribution as a normal distribution with the first standard deviation at 30 degrees. This distribution predicts that the front of the tank is more likely to be hit than does the cardioid distribution. Since a broader distribution is more difficult to protect, the broader distribution may be considered more conservative with regard to protection system design, and for this reason, the cardioid distribution was used in this study.

Defining the Frontal Arc

The frontal arc (FA) is the angular portion of the MBT most heavily protected. It is normally defined as the combination of two symmetrical angles, each placed alongside the hull with its apex at the rear of the hull and fanning away from the vehicle, as shown in Fig. 3. Alternative methods exist for defining the frontal arc. For example, the apex for each an-
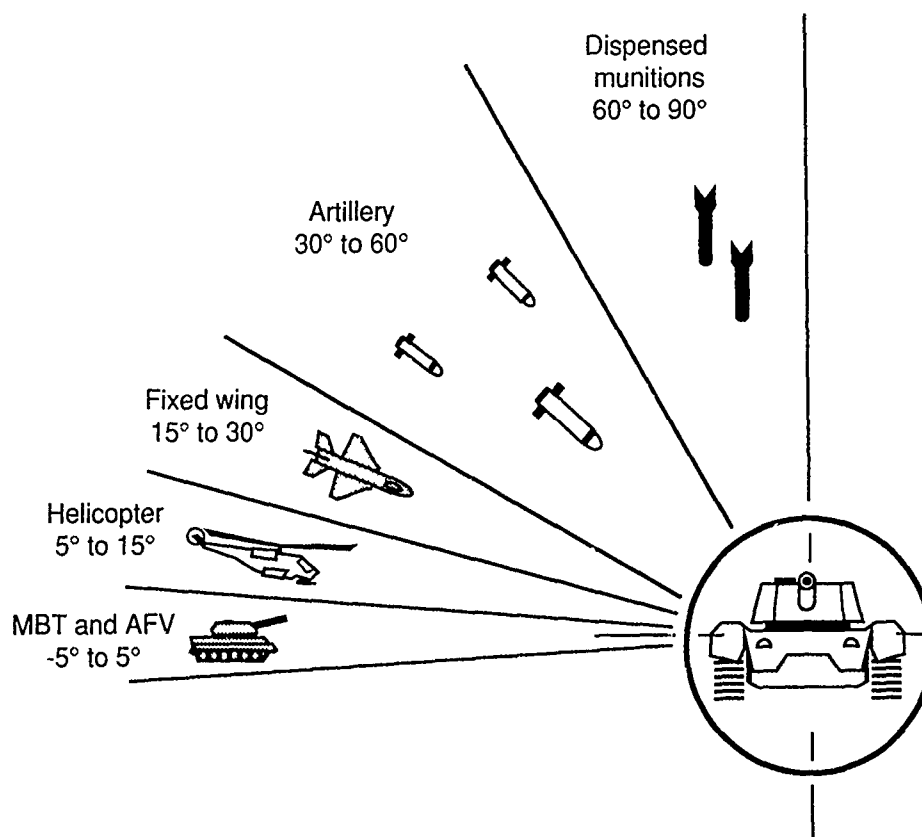
Fig. 1—Vertical threat envelope
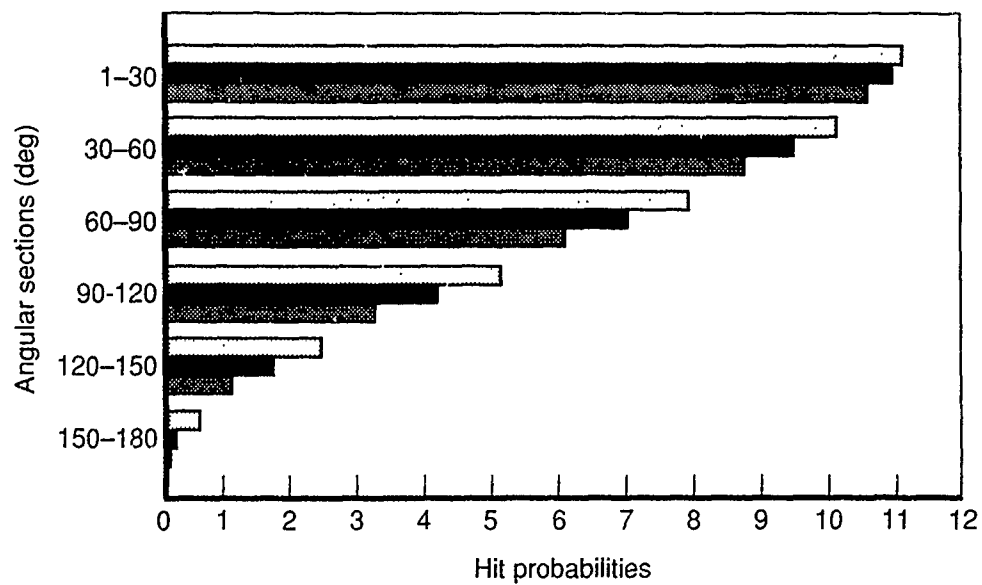
Fig. 2—Cardioid hit distribution for armored vehicles

Large helicopter/vehicle–mounted ATGMs

Tank–fired KE rounds

Hand–held ATGMs
and
heavy chain guns

Crew

Ammo

Engine

Hand–held ATGMs
and
heavy chain guns
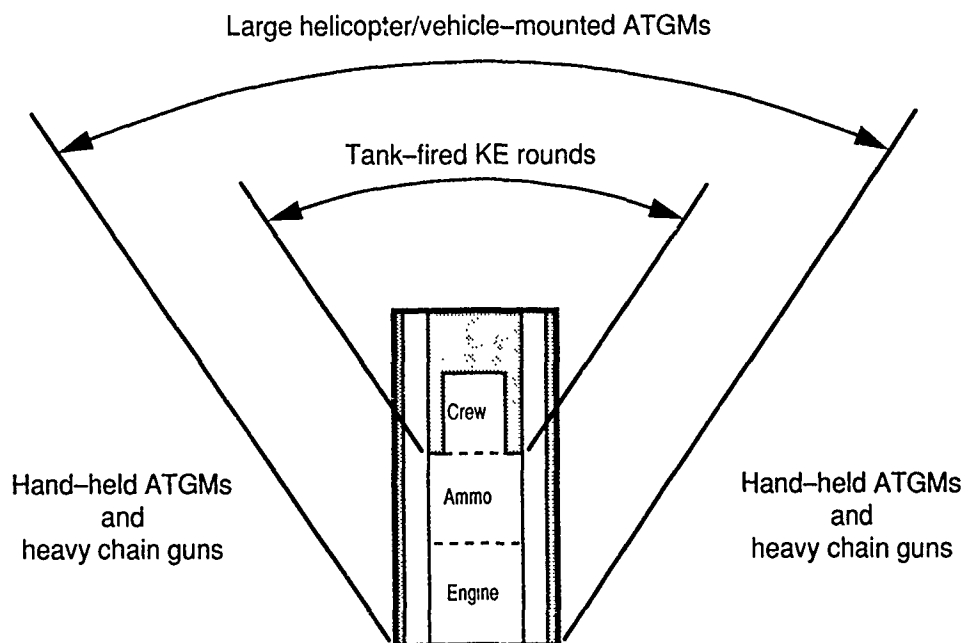
Fig. 3—Horizontal protected envelope

gle may be placed at the rear corners of the crew compartment rather than the rear of the vehicle. How one defines the frontal arc and its size is influenced by the threats and the protection priorities established. The protection priorities set for this study are as follows:

- Protect the crew
- Prevent a catastrophic kill
- Maintain minimal mobility (limp home capability)
- Maintain ability to fight (protect gun system)

In a sense, all of these priorities are dependent upon the first, protecting the crew. The crew is more certain to survive if, given a hit, the ammunition compartment does not explode. They have more of a chance of coming off the battlefield if, given a hit, the vehicle can seek some safer area, even if incapable of leaving the battlefield. Finally, the crew must be able to defeat the opposing forces if it hopes to survive in the long run. From this set of priorities, it follows that the crew volume should be the most well-protected space in the MBT, followed in turn by the ammunition compartment, the engine compartment, and the gun system.

The level of protection of the vehicle and compartments on the vehicle was defined with a vulnerability model developed at RAND called RAVUM. The impetus to develop a model rather than use an existing model such as VAST or SLAVE resides with the demands placed on such a model in the early design stage.

Most vulnerability models were developed to yield accurate vulnerability predictions of a given vehicle versus a variety of weapons. A three-dimensional geometric representation of the vehicle is generated along with its armor characteristics, the vulnerability of its internal

components, and the likely amount of spall a penetration would produce. The probability of killing the MBT when attacked from any position within a hemisphere is output.

The vehicle geometry and component placement used by, for example, VAST must first be constructed using a specialized solid modeling preprocessor, such as GIFT. GIFT creates the geometry file and stores it in terms of shot lines—rays a shot would follow through the vehicle.

Developing GIFT files and running VAST or SLAVE require a highly qualified specialist. These programs consume vast amounts of computing power. The U.S. Army's Ballistic Research Laboratory, for example, runs their models on one of the more recent versions of the Cray supercomputer. The most computationally intensive portion of developing a model is creating new geometry files with GIFT. Because the early design phase of a project could reasonably be expected to examine a large number of different geometries, costs could accumulate rapidly.

In summary, the large vulnerability analysis programs were developed for detailed analysis of final design considerations; they are poorly suited for generation of the large number of design options required in early design stages. Not only would it be expensive to do so, but the output is far more detailed than necessary and therefore cumbersome.

For these reasons, RAND developed a simple vulnerability analysis code, RAVUM, for use in the preliminary design stage. Three major simplifications were employed.

- The three-dimensional geometry of the MBT is constrained to consist of rectangular elements only.
- Only horizontal shots were considered.
- Only the damage to relatively large compartments, rather than individual components, is considered.

These three assumptions and others greatly simplify the required coding and make the resulting model more user-friendly. For example, RAVUM has both graphical input and output, and one complete run requires roughly 10 seconds of computation time on a 20286 machine.

Certain limitations to the RAVUM model deserve mention:

- Horizontal shots only
- No spall generation
- Not effective for marginally armored areas

The last point indicates that the model would not be able to predict the vulnerability of an area in which the penetrator just barely enters a compartment. All penetrations are assumed to be complete, and penetrators are assumed to completely damage the compartment they enter. Since a designer is unlikely to design an armor to be penetrated, this drawback was not considered critical for design purposes. However, as the design approaches the final phase, a more accurate model such as VAST should be used for verification purposes and as an aid in component placement.

The basic vehicle from which variations were developed is outlined in Fig. 4, generated by RAVUM. The frontal armor compartment is 1.35-m thick and a skirt extends within the
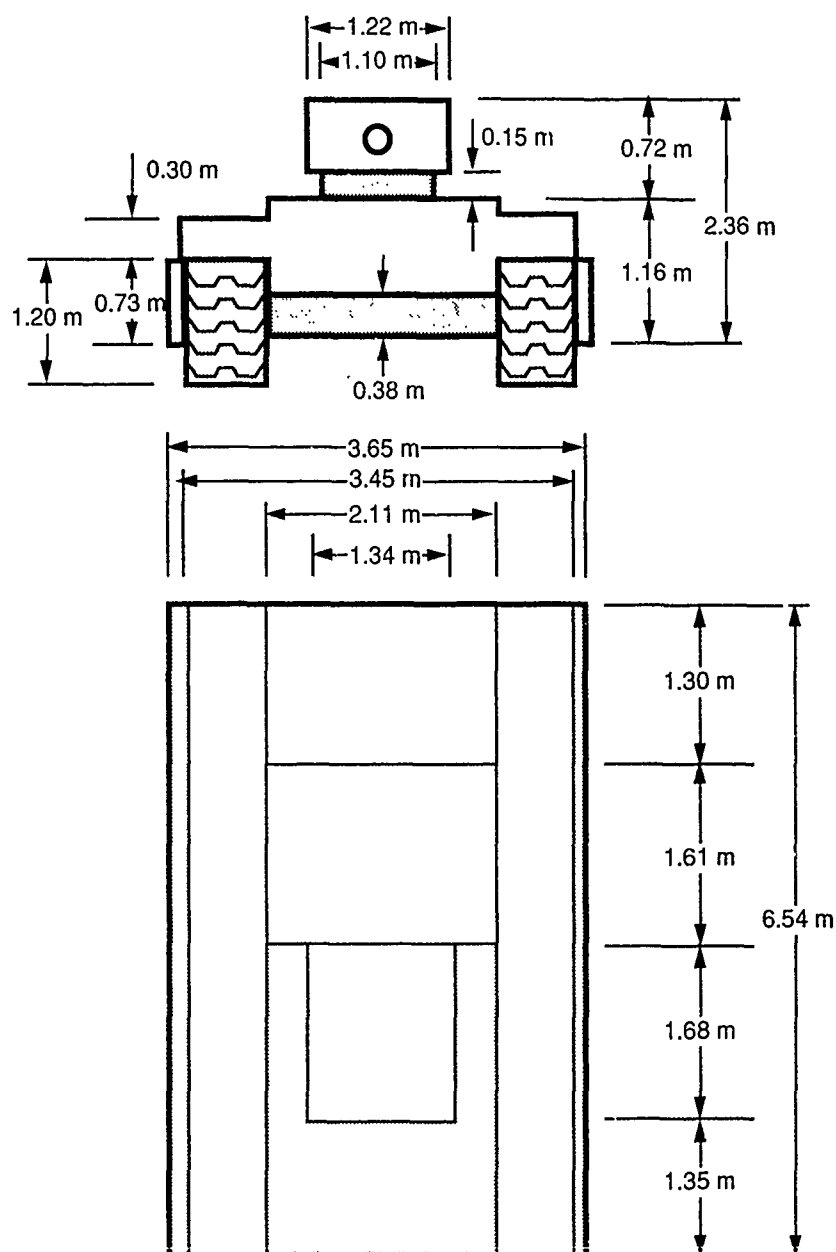
Fig. 4—Basic hull dimensions used in RAVUM

hull to protect the crew compartment, which is 1.7-m long and as wide as the hull less the side hull armor thicknesses. The ammunition compartment is 1.6-m long, and the engine compartment is 1.9-m long.

The skirt is split, with the CE armor exterior to the treads and the KE armor interior. A split skirt was seen as the only method to gain a reasonable frontal protection arc within the hull without widening the vehicle beyond acceptable limits.

The frontal armor is divided into two armor plates, an upper and a lower glacis. The upper glacis is designed to protect against both KE and CE threats, whereas the lower glacis (shaded in Fig. 4) protects against CE threats only. The height of the lower glacis was initially set at 0.5 m.

The turret is also protected by 1.35 m of armor except for the exposed shot trap and gun barrel. The width of the turret is defined by the turret frontal arc and the interior width, which is initially set at 0.75 m. The turret interior space is 2.1-m long and 0.76-m high.

The main parameters to be varied in the RAVUM computations are the hull frontal arc, the turret frontal arc, the side hull armor length, and the lower glacis height. As these parameters are varied, the cardioid-averaged vulnerability and armor mass for the vehicle are calculated. A spreadsheet program was employed to automate the armor mass calculations. Again, the primary purpose of this exercise is to determine the values for the parameters that produce the most protection for the least armor mass.

In this optimization, the KE mass efficiency is assumed to be 2 and the CE mass efficiency 10. A medium range threat of 750-mm RHA was chosen. Two parameters are typically used for measuring vehicle vulnerability. The first is the probability of killing the vehicle given that it is hit ($P_{k/h}$). The second is simply the probability of killing the vehicle (P_k). Using P_k as a measure gives a better sense of battlefield vulnerability. However, P_k is dependent upon the size of the vehicle, the accuracy of the attacking system, and the aim point, which led us to use $P_{k/h}$ as the measure of vulnerability.

We assumed the accuracy of the attacking KE weapon to be half a milliradian and that it was fired from a range of one kilometer. The aim point was set at 0.2 m below the turret ring. The effects of CE weapons were also analyzed, especially in preparing input for wargaming analysis; however, because KE armor more strongly influences the final weight of the vehicle, KE threats were emphasized.

Side hull armor length was the first parameter varied. The minimum length ran the length of the crew compartment; the maximum length ran the length of the vehicle. We found that $P_{k/h}$ changed very little as the side skirt was lengthened for frontal arcs below 90 degrees. The reason for this rather unexpected behavior is that, even as the shot line swings from a frontal to a side shot, the aim point remains centered mostly upon the crew compartment. Therefore, fewer shots are likely to hit the ammunition or engine compartments, and the $P_{k/h}$ is only slightly decreased when these sections are further armored by increasing skirt length. Of course, this effect would be lessened if the aim point were moved off the center of the target or if the CEP were increased. In fact, the $P_{k/h}$ of a vehicle would be increased if gunners always fired at the rearmost section visible in their sights. However, since such behavior would certainly reduce the probability of a hit, it would be a dubious practice and not one seriously considered in this study.

The effects of variation of the other two parameters, the hull frontal arc and the lower glacis height, may be seen in Figs. 5, 6, and 7. Vulnerability is listed along the ordinate and

frontal arc along the abscissa. Crew and turret compartment vulnerabilities are shown along with the vulnerability of the entire vehicle. Armor masses for the given configurations are listed above the bars.

The ordinate in these figures is a cardioid-weighted $P_{k/h}$. This value accounts for the relative importance of frontal armor as compared to flank or rear armor. The marginal effectiveness of increasing frontal armor from 0 to 1 deg is therefore much greater than an increase from 179 to 180 deg.

The standard frontal arc for most MBTs is 60 deg. In Fig. 7, the armor mass for a vehicle with a standard frontal arc is shown to be 24.5 tons (22.2 metric tons or tonnes). If we set a constraint of roughly 28 tons (25 tonnes) for the maximum armor weight, then for a lower glacis height of 0.5 m, the maximum allowable frontal arc is just under 100 deg. For a 0.3 m height, it is roughly 60 deg, and for no lower glacis, it is under 40 deg. In effect, by armoring the lower portion of the glacis against CE only, we can greatly widen the protected frontal arc.

For the armor mass constrained case, the optimal solution is reached at a lower glacis height of 0.5 m and a hull frontal arc of 91.5 deg. Here, the $P_{k/h}$ (cardioid-weighted) is 57.2 percent for the vehicle, 52.7 percent for the crew compartment, and 49.5 percent for the turret. Note that even though the turret is protected only with a 0 deg frontal arc, it is still less vulnerable than the crew compartment. This behavior stems from the relative robustness of turret components versus the crew and crew compartment components. Given a hit and penetration, turret components are assumed to be more likely to survive than crew compartment components.
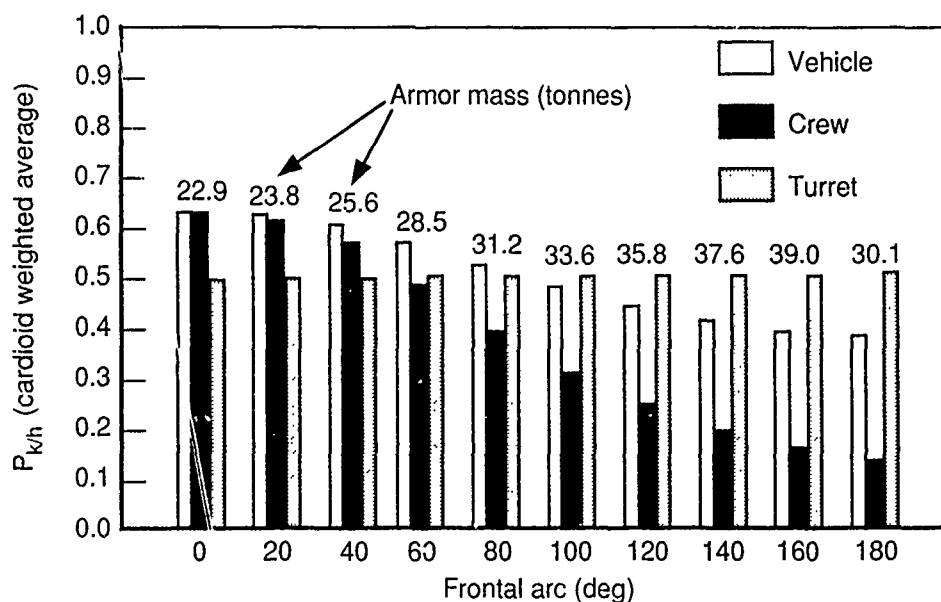
Fig. 5—MBT compartment vulnerability
(turret arc = 0; lower glacis height = 0)
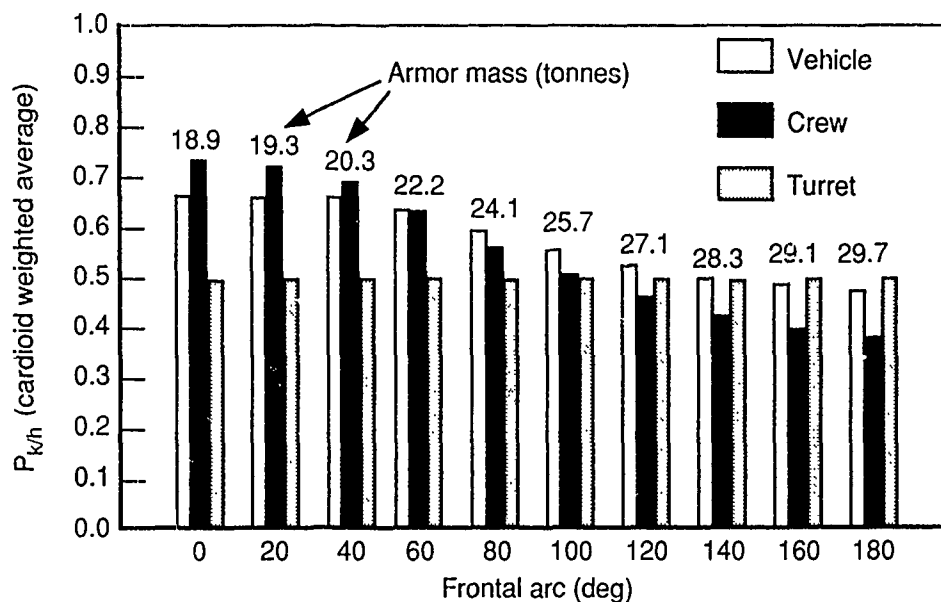
Fig. 6—MBT compartment vulnerability
(turret arc = 0; lower glacis height = 0.3 m)
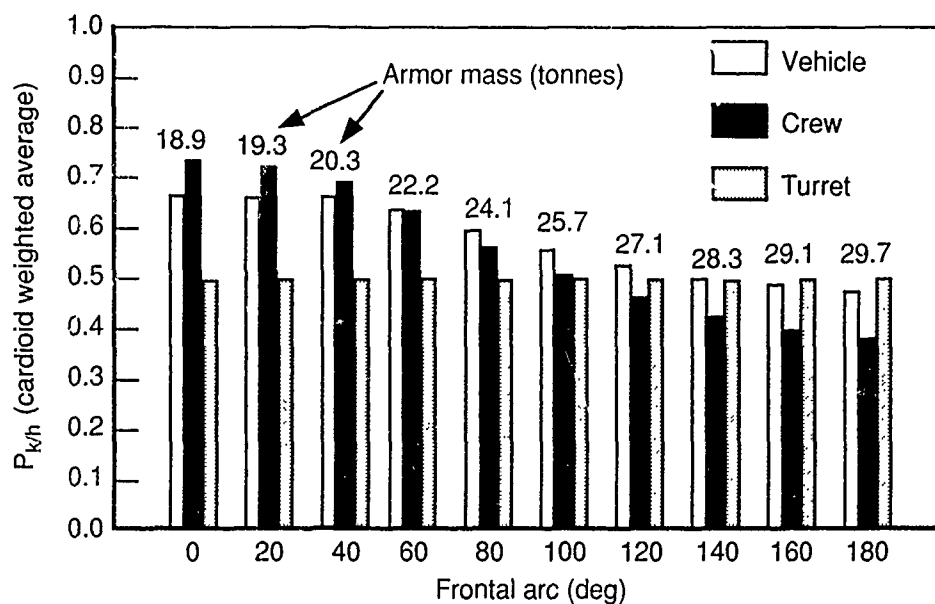
Fig. 7—MBT compartment vulnerability
(turret arc = 0; lower glacis height = 0.51 m)

Since the crew compartment is listed as being a higher protection priority than the turret, one may wish to release the armor mass constraint and replace it with the constraint that the crew compartment be the most survivable part of the vehicle. For example, let us choose that the crew compartment must be 10 percent more survivable than the turret, $P_{k/h}$

= 44.5 percent. For this case, a lower glacis height of 0.5 requires a frontal arc of 135 deg, which yields a vehicle vulnerability of 50.3 percent and armor mass of 31 tons (28 tonnes). For a lower glacis height of 0.0 m, the required frontal arc is 72.2 deg, producing a vehicle vulnerability of 54 percent for an armor mass of 33 tons (30 tonnes). Therefore, a lower glacis height of 0.5 m again gives the better solution.

Another important constraint is interior space restriction. As the hull arc is increased, the crew compartment width is reduced. If we set the crew compartment width of 1.6 m as a minimum, the optimal solution may again be found, but it is also dependent upon how the skirt is split and the space efficiency of the armor.

We are assuming that the skirt is split with the KE armor interior to the trackwells. The split skirt concept allows maximal interior volume to the rear of the crew compartment while allowing explosive armors to be used in the exterior skirt portion. The maximum allowable frontal arc is then a function of the space efficiency of the KE armor and the threat, as shown in Fig. 8. The required amount of KE armor may be calculated from the mass efficiencies of the KE and CE armors and the KE threat. For a maximum crew compartment width of 1.6 m, a residual KE threat of 600 mm, and a space efficiency of 1.4, the maximum allowable frontal arc is 71 deg. Unfortunately, modern armors tend to trade space for mass reductions, and usually have space efficiencies below 1. The 1.4 space efficiency in this example stems from the assumption that in space-restricted areas a heavy metal armor will be used. Heavy metals such as tungsten or depleted uranium are roughly twice as dense as steel. Using the modified Bernoulli model for armor penetration yields a space efficiency of roughly 1.4 and a mass efficiency of 0.7.
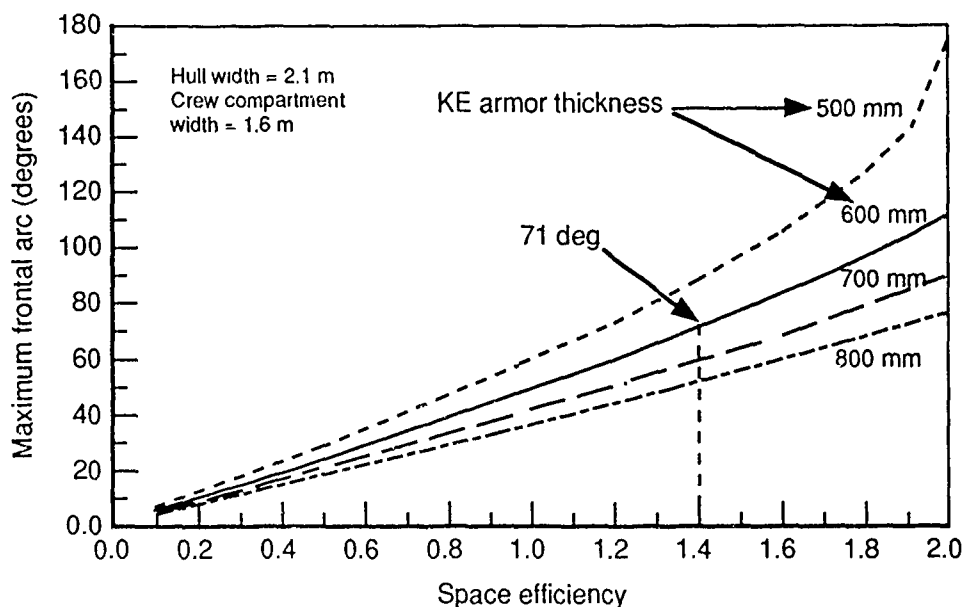
Fig. 8—Maximum frontal arc as a function of space efficiency

If the only constraint is a maximal angle of 71 deg, then an MBT with no lower glacis plate (the upper glacis would extend to the bottom of the hull) would give the highest protection level. Such a protection scheme would weigh 30 tonnes; the crew vulnerability would be 43 percent and the vehicle vulnerability 54.3 percent. If the added constraint of a maximum armor mass of 25 tonnes is added, the optimal solution may be interpolated from the charts. ᵀhe lower glacis height would be 0.38 m for a frontal arc of 71 deg, the crew compartment survivability 53.8 percent, and the vehicle survivability 58.9 percent.

For the above configuration, a more detailed analysis was conducted to determine survivability of the crew, ammunition, and engine compartments as a function of shot line azimuth. As can be readily seen in Fig. 9, the $P_{k/h}$ of a two-man MBT with a 71-deg frontal arc increases dramatically once the attack azimuth overtakes the protection zone provided by the frontal arc. The crew compartment becomes particularly vulnerable, especially when compared with the turret vulnerability.

The high crew vulnerability outside the frontal arc is somewhat alleviated by the decreasing probability of a hit on the crew compartment as the attack azimuth approaches 90 deg. In Fig. 10, the probability of hits for the turret and vehicle are shown to be maximal at 90 deg, but the crew compartment P_h is minimal at that point. This behavior derives from the the crew compartment swinging off the aim point as the attack azimuth is increased.

This lower P_h for the crew compartment at the perpendicular tends to decrease the overall probability of a kill for that compartment outside the frontal arc, as shown in Fig. 11. Here the P_k for both the vehicle and turret remains almost constant outside of the frontal arc zone.
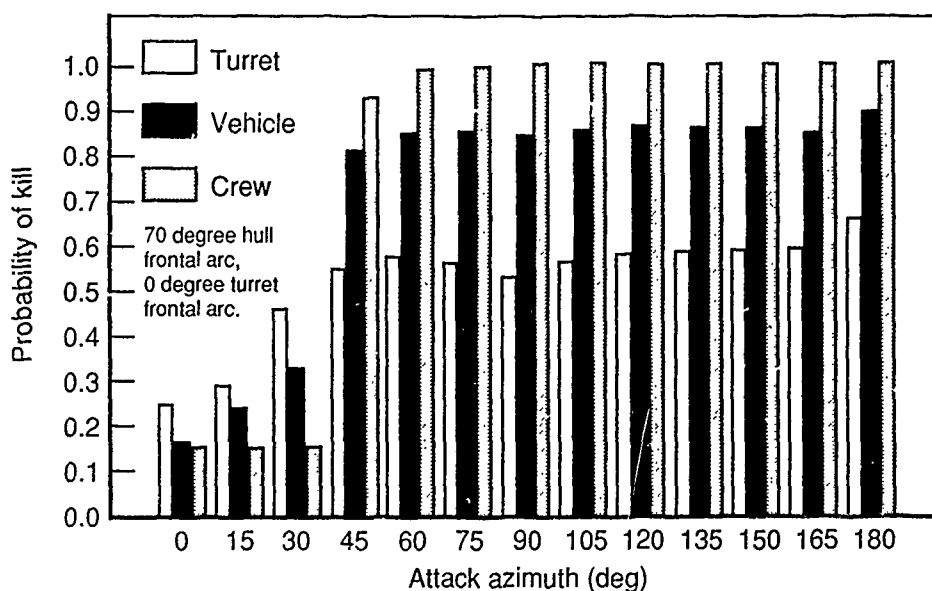
Fig. 9—Probability of kill given a hit for two-man MBT
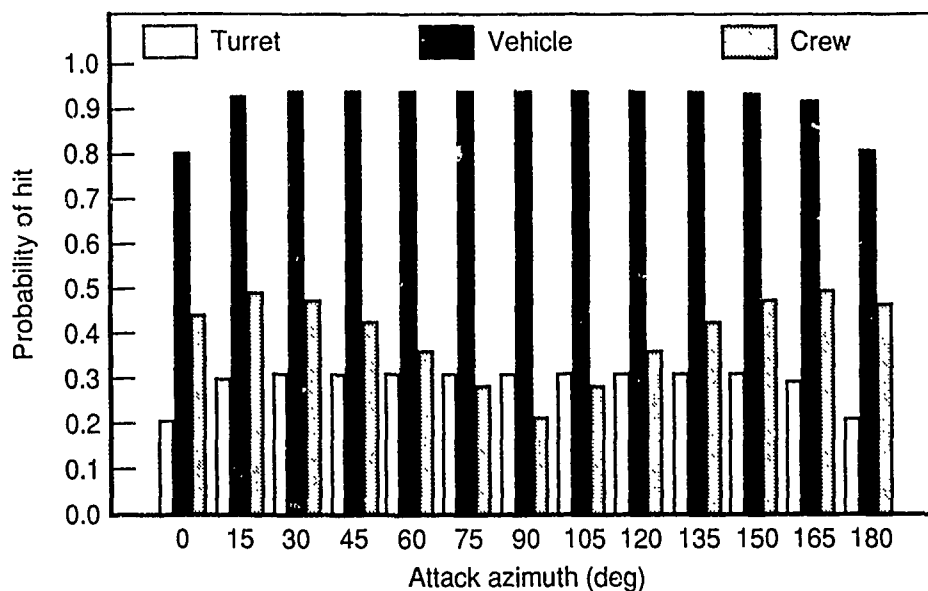
Fig. 10—Probability of hit on two-man MBT
from tank gun at 1 km range
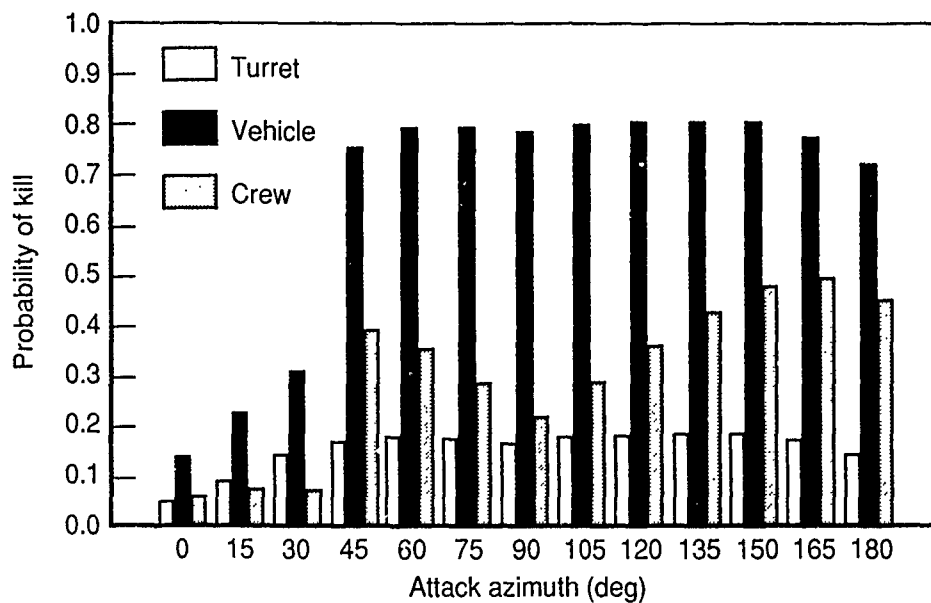
Fig. 11—Probability of kill of two-man MBT
from tank gun at 1 km range

However, the P_k for the crew compartment decreases to a minimum in this zone at 90 deg and then increases to a maximum near the rear of the vehicle.

Figure 11 is misleading in one sense—it would seem to indicate that a rear shot presents the greatest opportunity for the crew compartment to be hit and penetrated. However, the probability of a shot occurring in the rear region is very low. In Fig. 12, the P_ks for the vehicle, turret, and crew compartment are shown as weighted by the cardioid distribution. The weighted P_k for the crew compartment again increases dramatically just outside of the frontal arc. As the attack azimuth increases beyond 75 deg, the weighted P_k decreases to a relatively low level and then slowly decreases to zero at the rear of the vehicle. Therefore, the region in which the crew compartment is most likely to be penetrated is from just past the frontal arc to roughly 75 deg.

Protecting the Top, Bottom, and Sides of an MBT

Although the frontal glacis and frontal turret armor represent a significant amount of mass, the majority of armor mass is contained in other areas. Besides the top, bottom, and sides of the vehicle, there are armored hatches, grilles, sensor cages, and bulkheads. Grilles, for example, generally require three times the mass for an equivalent protection level as armored plate.

The most prevalent threat to the MBT today is the antitank guided missile (ATGM). These weapons carry a chemical energy warhead, generally a shaped charge (SC), and vary in size and lethality from large vehicle and helicopter-mounted versions to smaller hand-held weapons.
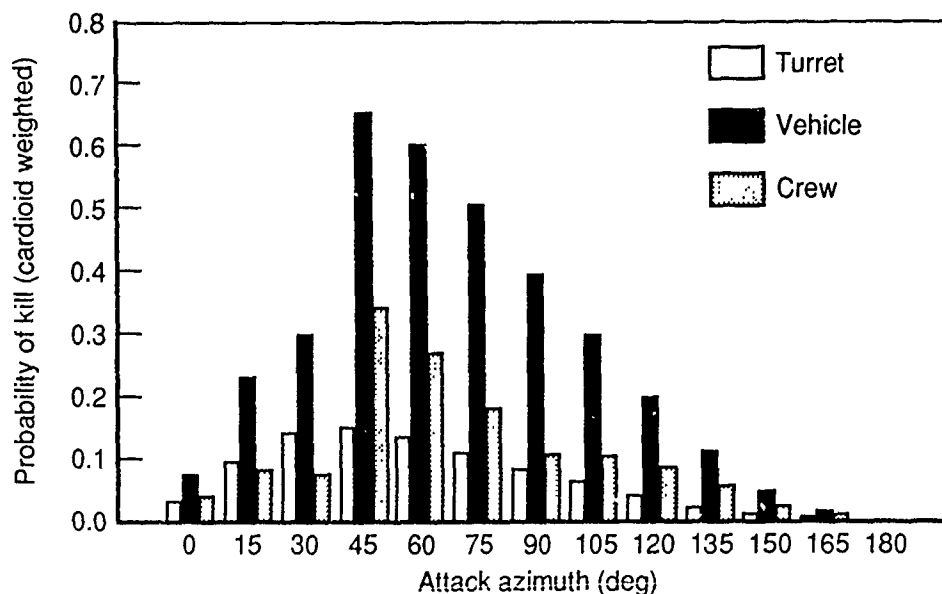
Fig. 12—Cardioid weighted probability of a kill given a shot
for a two-man MBT from tank gun at 1 km range

The entire vehicle sides need to be protected against large CE threats over the frontal arc for the simple reason that CE munitions are quite common on the battlefield, and many more CE than KE shots will be fired at and hit the MBT. The entire side of the MBT must be protected from hand-held ATGMs and larger caliber automatic cannons at all azimuths, if possible. Space limitations make these protection goals somewhat more difficult to achieve below the sponson level.

Space considerations present a much more difficult constraint for top protection. The top of the MBT is littered with hatches, grilles, blow-off panels, and externally stowed material. Even for a vehicle not constrained in armor mass, the practical difficulties of armoring the vehicle top are, in many cases, insurmountable. Therefore, means other than armor must be found for countering the top attack threat. Since the most lethal top attack threat comes from "smart" munitions, one likely avenue of reducing the threat would be to reduce the signature of the vehicle in the proper wavelengths. The two most common threat sensor wavelengths are in the millimeter and infrared (IR) regimes.

The infrared signature of the MBT is created by a variety of sources: the engine, the gun, and the environment. The engine not only creates a large amount of heat that must somehow be expelled from the vehicle, but its grille spaces and mufflers often present the largest IR signature. The key to handling the engine signature is therefore to shield or cool the vents, muffler, and engine deck until the heat is safely dispersed into the atmosphere.

Although the gun presents a large thermal signature after it has been fired several times, this signature causes little concern. First, it is unlikely that top attack weapons will be employed when the battle is engaged since such weapons cannot usually discriminate between friend and foe. Second, firing the gun itself creates such noise, flash, dust, and smoke that the thermal signature pales in comparison.

The environment may also create an IR signature that distinguishes the MBT from the background. For example, the surface of the tank tends to remain hotter than its surroundings at night, and the thermal emissivity of steel differs from that of dirt or sand. Tailored emissivity paints and covers can alleviate this signature somewhat. However, such covers must be relatively thin, light, and durable. They must also operate under normal, dirty battlefield conditions.

Millimeter wave (MMW) sensors are somewhat harder to counter since they are active—they send out a measured signal to discriminate objects. One method of reducing their effectiveness is to modify the external geometry of the tank to minimize its reflectivity in the MMW regime. For example, trihedral corners should always be avoided and perpendicular edges should be minimized. Coverings may be applied to reduce the MMW signature, but here again, they must be thin, light, and durable.

Armor Summary

The primary purpose of this study was to develop tools for properly assessing armor requirements for future MBTs. The tools were then applied to the specific case of the RCV, and an optimal armor configuration for that vehicle was generated.

The methodology for optimizing armor configurations begins with defining protection priorities. Without a clear set of priorities, there can be no armor tradeoff analysis. After priorities are set, the threat and available armor technology may be defined. In this study, we chose to define broad parametric threat and armor technologies. In the early design phases, choosing more specific parameters could lead to misperceptions since the first vehicle may not roll off the assembly line for many years. Once objectives, threat, and armor technologies are defined, a flexible vulnerability analysis program such as RAVUM may be used in conjunction with practical constraints to arrive at the optimal solution. The practical constraints are normally volume and weight limitations.

The above methodology was applied to the RCV—a two-man MBT concept with a central remote turret and rear engine described in Sec. IV. The armor mass was constrained to 28 tons and the volume was constrained by practical design aspects. RAVUM was then employed along with the mass computation program to determine a candidate armor configuration.

One weakness of this methodology is that top and bottom protection are defined *a priori*. The armor in these sections was basically determined as part of the vehicle configuration process. Although threat and armor technology were considered in our definitions, the logic of practical considerations was dictatorial, especially for the hull and turret decks. These issues will be discussed in more detail in the configuration section.

In the end, the answer to top protection may not lie with armor but with low observable (LO) technology. Since the most virulent top threats of the future will be those of the "brilliant munition" age and these munitions rely upon their sensing capabilities, it stands to reason that one may be able to defeat the threat by defeating the sensor. Although this begins a countermeasure/counter-countermeasure contest, that would be little different from today's armor/threat contest except that, perhaps, Western technology could be better employed to its advantage.

Various LO appliques may be developed in the future, but the MBT designer should take steps in his current designs to allow for future LO technology. For example, trihedral corners and perpendicular intersections should be avoided, and space should be left free on the hull for LO appliques.

WEAPONS SYSTEMS

An important mission for both the MBT and the light tank is to defeat enemy MBTs. Traditionally, MBTs employ a large antitank gun in this role, and light tanks use either guns or missiles. In this section, line of sight (LOS) gun and missile systems that use the kinetic energy of the round to defeat armor are considered for use in both MBTs and light tanks.

Gun Systems

Four general types of gun systems were reviewed as candidates for the main MBT armament: solid propellent (SP) guns, liquid propellent (LP) guns, electromagnetic (EM) guns, and electrothermal (ET) guns. Antitank guns are powered by solid propellents. Since WW II, SP antitank guns have grown in size and mass; in this report, it is assumed that future

SP guns will be even larger and heavier. Liquid propellant and electric guns are in development. Possible outcomes of their respective development programs are estimated at the end of this section.

The following parameters influence the choice of a gun system for a given mission:

- Muzzle energy
- Firing rate
- Number and mix of ready rounds
- System accuracy
- System size and weight
- System vulnerability
- Development time available
- Cost
- Reliability, availability, maintainability

For a future MBT, the overriding requirement for the gun system is that it defeat enemy tanks. For the future threat, this mission will require a higher muzzle energy than is available from today's most advanced antitank guns. The challenge is to develop a gun with a higher muzzle energy while not adversely affecting other gun parameters such as firing rate or accuracy.

1. Solid propellant gun systems

The Soviet Union currently fields the largest antitank gun systems. Their latest production model tanks are equipped with a 125-mm bore diameter gun that is approximately 5 m long. Many observers expect that the next generation of Soviet gun will have a 135-mm caliber. In the West, the most advanced antitank gun is the Rheinmetall 120-mm smoothbore gun, designated as the M256 in U.S. inventories.

Gun and ammunition sizes. The M256 produces 9 MJ of kinetic energy at the muzzle, a portion of which is transferred to the penetrator. Since the expected muzzle energy for many LP and EM gun systems is projected to be over 18 MJ, double that of the current 120-mm system, a conceptual 20 MJ SP gun was posited for this study.

The 20 MJ SP gun was scaled up from the 120-mm gun using accepted gun sizing principles and assuming a constant specific energy for the propellant. The chosen muzzle velocity was 2 km/sec, which implies a projectile mass of 10 kg. Assuming that roughly half of that mass is sabot, the actual long rod penetrator would weigh 5 kg. If one further assumes a limiting length-to-diameter (L/D) ratio of 30 and that the penetrator is composed of depleted uranium (DU), then the length of the penetrator would be roughly 700 mm. Adding a windshield and fin structure would add slightly more length. The final penetrator length for this study is therefore assumed to be roughly 750 mm.

Launching a 5-kg rod at 2 km/sec would require nearly 20 kg of propellant, occupying roughly 17 liters of space. If the diameter of such a projectile is limited to nominally 135 mm, the overall round length would be over 1.5 m. This necessitates the use of two-piece ammunition.

Autoloaders. To maintain current firing rates with two-piece ammunition, an autoloader must be employed. For this study, a firing rate of six rounds per minute was nominally required.

Autoloader concepts may be placed into two categories: cannister round and bare round loading systems. The advantage of bare rounds is that more may be stored within the vehicle. Cannister rounds contain both ammunition pieces side-by-side in a single container. Cannister rounds offer several positive attributes. (1) They are easier to handle in the logistics train, allowing faster, possibly automated, reloading and pallet storage and transport. (2) They allow simpler autoloader design and function. (3) They offer lower vulnerability and greater safety.

The type of autoloader depends greatly upon the placement of the gun. The three options for gun placement are external to the hull, within a turret, and fixed or semifixed within the hull. Most MBTs place the gun within a manned turret, although the gun may also be placed within an unmanned turret, often called a remote turret. The Swedish S-tank places the gun rigidly within the hull. Experimental tanks such as the Elke have placed the gun completely outside the hull on raisable platforms.

The type of autoloader also depends upon the placement of the ready round magazine. The choice is either to place the ammunition within a turret bustle or to transfer it from hull to breech. Placing the ammunition within the bustle would seem to negate many of the advantages offered by an external or remote gun. A sufficient store of ready rounds would comprise a large bustle. It would therefore have a relatively higher probability of a hit and need to be armored, increasing the weight of the vehicle.

Loading an external gun from the hull presents several problems. The system would tend to be complex and the ammunition transfer method would be vulnerable. One example of such a system is the Swedish loading tray, diagrammed in Fig. 13. In this concept, the ammunition magazine is contained in a hull bustle behind the engine. A loading tray is attached to the turret ring. It picks up a round from the magazine and traverses to the breech position. The round is then loaded into a rotating breech.

The advantages of a traversing tray loader are:

- Ammunition is fully compartmentalized
- No gun indexing is required
- A large number of ready rounds is available

In addition, the ammunition is taken off the aim point and placed external to the hull, which should greatly enhance the survivability of the vehicle.

The primary disadvantage of the traversing tray concept is its complexity. It would be particularly problematic for two-piece ammunition. The pieces would need to be joined before loading, creating a very long hull overhang, or a complex tray/breech system would need to be invented. For example, the ammunition cannister could be delivered to a turret bustle equipped with an autoloading system that rams each piece separately.

Design difficulties are fewer for the remote gun since it provides easy hull access. For the remote gun concept, the gun is mounted in a turret extending into the hull. The autoloader could then be contained within the turret basket. This type of loader would potentially offer several advantages:

- Well-protected ammunition and autoloader mechanism
- Large number of ready rounds

1. Load tray

2. Raise tray

(Top view)

3. Rotate gun
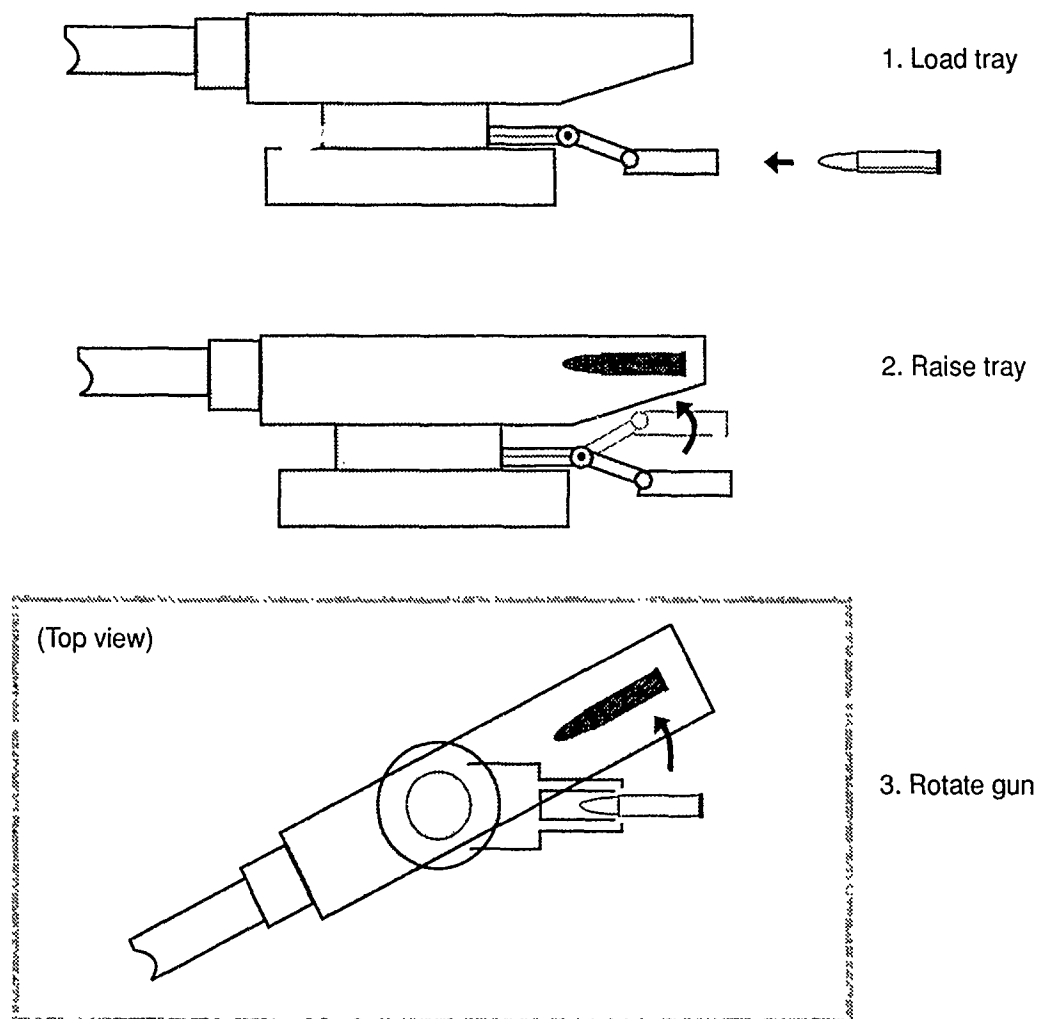
Fig. 13—Tray-type autoloader

- Relatively simple autoloader design
- Two-piece ammunition handling

Another advantage of the remote gun is that the turret ring may extend the width of the hull, since it would not interfere with the loading tray.

Several disadvantages also accrue. Placing the ammunition in the center of the hull consumes a large amount of hull space and places the ammunition at the center of the flank aim point. Also, a hit in the ammunition compartment. if not properly vented, could completely destroy the vehicle.

Hull loaders were examined for both bare rounds and cannister ammunition. Concepts from Ares,[1] FMC,[2] and Emerson Electric[3] were considered for cannister round autoloaders. For the bare round designs, concepts from FMC, Western Designs, and General Motors were considered. Of these concepts, the Ares design for containerized rounds was judged the most appropriate for our analysis. It was therefore chosen as the base from which the autoloader discussed in the concept section was derived. A sketch of the two-piece ammunition container as proposed by Ares is shown in Fig. 14. It is 850 mm long, 160 mm wide, and 340 mm tall.

The bulk of the propellent is contained in one cavity and the warhead, with more propellent in another cavity. The small hook shown in the lower right-hand corner of the side view is necessary for proper autoloader function.

The Ares autoloader was slightly modified to the form shown in Fig. 15. It consists of a ring of ready rounds mounted on a rotating carousel that is contained within the turret basket and rotates with the gun. It can carry several types of rounds.

As shown in Fig. 16, ammunition is carried from the basket to the turret on an elevator. The elevator is a simple double-link chain that pulls the round along a guide. The round is pulled from the carousel into ramming position. The proposed rammer is a double chain rammer.[4] For the two-piece ammunition design, one piece is first loaded, the elevator is
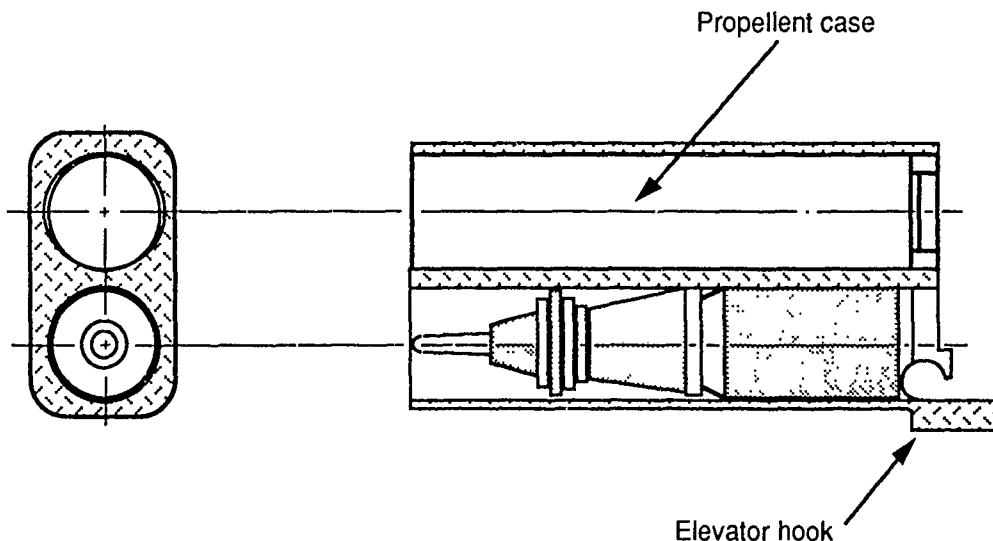
Fig. 14—Two-piece ammunition container

[1]James E. Wildman, *Conceptual Design for 120-mm Improved Conventional Armament System (ICAS) Autoloader*, Ares Inc., ARLCB-CR-84012, February 1984.

[2]B. O. Goodell et. al., *Conceptual Autoloader Design Study for Future Armament System for Combat Vehicles (FASCV)*, FMC, ARLCB-CR-84011, February 1984.

[3]*Improved Conventional Armament System Autoloader*, Emerson Electric Company, ARLCB-CR-84010, February 1984.

[4]Other rammer types, such as a ribbon rammer, may also be used. The double-chain rammer used here was part of the proposed Ares autoloader system.

Case ejection

Chain rammer

Ramming
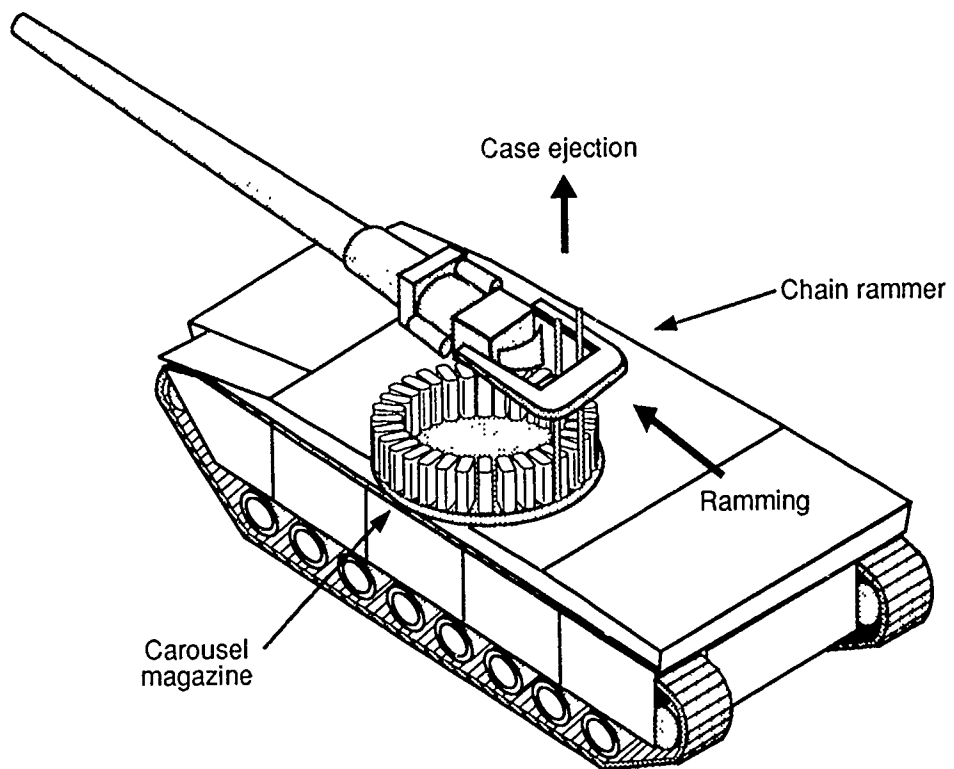
Carousel
magazine

Fig. 15—Carousel autoloader
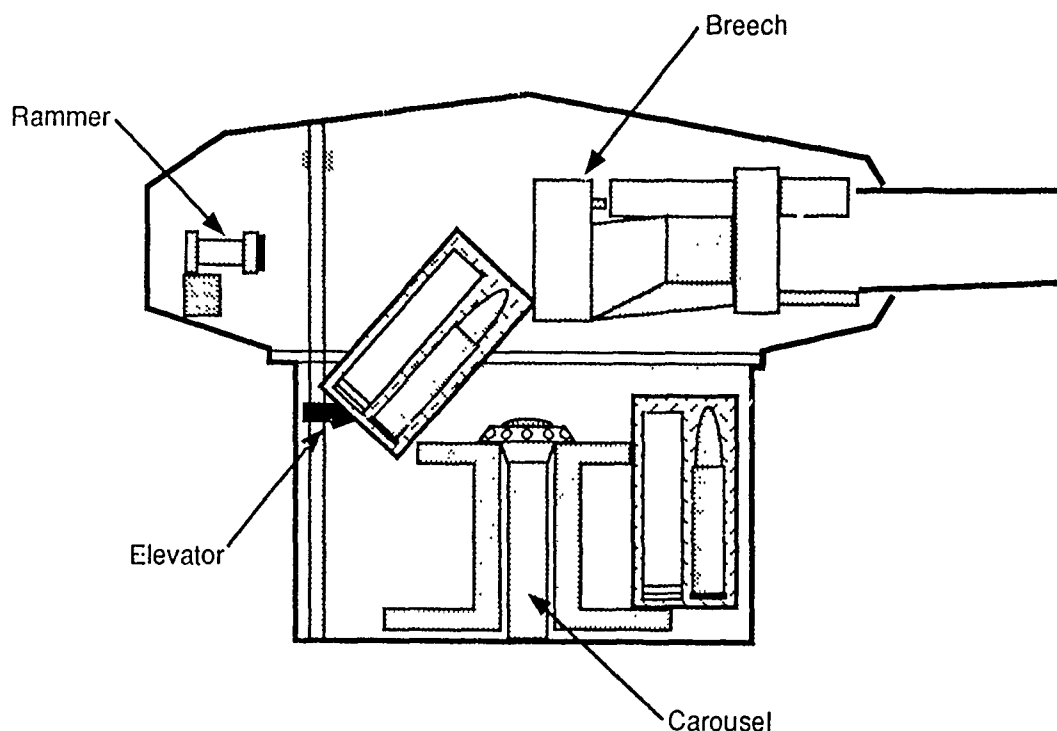
Fig. 16—Carousel autoloader mechanism

raised, and the second piece is then rammed. The elevator continues to rise until the empty cannister is ejected from the top of the turret.

Rounds may also be downloaded if the rammer and round pieces are equipped properly. At least one spent cannister may be retained in the carousel for downloading. Given the size of ammunition and the confined quarters of the turret and turret basket, it would not be feasible for this system to have a manual backup.

2. *Liquid propellent gun systems*

Liquid propellent systems are similar to SP systems in that they use the thermal energy released from a chemical reaction to power a projectile. The primary difference between the two is that liquid propellents can be stored separate from the warhead and pumped to the breech on demand.

The advantages often cited for LP guns are:

- Lower vulnerability
- Higher rate of fire
- More flexible integration
- Simpler autoloader
- Lower peak pressures and accelerations
- Less muzzle flash
- More manageable logistics

Most of the cited advantages other than that regarding peak pressures relate to system integration and overall system utility rather than to the antiarmor performance of a given round. A single shot from an LP gun is not projected to be any more accurate or lethal than a future SP gun.

However, it seems likely that an LP gun could at least equal the performance of a SP gun, and it could offer more performance growth as traveling charge technology is more fully developed.[5] Also, since the LP gun does not require two-piece ammunition, it could be more easily integrated into an external gun configuration.

The U.S. Army is developing LP guns for antitank use. The program is being funded primarily with Balanced Technology Initiative (BTI) funds, and it is not clear whether the Army would continue the program if these funds were no longer available. Two industrial teams, one led by Royal Ordnance and the other by General Motors, recently completed an integration study as part of the development effort. Both contractors concluded that MBTs using LP guns as their main armament offer several significant advantages over MBTs with SP guns.

The next phase of the LP gun development effort entails both teams developing brass board guns up to 140 mm in caliber. They will also be further detailing their overall MBT configuration designs. Indeed, since many of the hoped for advantages associated with LP guns reside in vehicle integration, any serious LP development program must consider both the technology and the integration.

There are several difficulties or disadvantages associated with LP guns. First, they represent a new technology still in the developmental state and are therefore largely untested. Second, the breech is larger than that for a SP gun, and the gun is heavier. Third, the gun system itself is more complex, although the autoloader should be simpler.

For a conventionally designed MBT with a manned turret, the wider breech causes a subsequent widening of the turret. The same is true of a remotely located gun. However, because the turret begins from a much smaller size, widening it tends to be more acceptable, although it would still present difficulties regarding hull intrusion when in full elevation.

Liquid propellent guns tend to be less efficient than SP guns, and the LP has less energy per unit mass. However, the LP has higher energy per unit volume, and it is easier to store than solid propellents. The designer has the flexibility of locating the LP bladder in almost any shaped space.

An often cited advantage of LP systems is that the propellent can be stored so that it will not detonate or burn if hit by the primary penetrator, although the LP lines and pumps may still present a hazard. Even low vulnerability (LOVA) solid propellents may be expected to ignite given a direct hit. This advantage of LP is all the more intriguing since the ammunition compartment is at the center of the aim point for side shots, and it is currently impossible to adequately armor any compartment for a flank shot. Therefore, the overall survivability of the vehicle could be dramatically increased by employing low vulnerability liquid propellents.

However, significant questions remain as to whether LP propellents could be stored in a practical manner while retaining their low sensitivity to ignition. The main concern arises

---

[5]Traveling charges are also possible with SP guns, but would be more cumbersome.

from containment. Liquid propellents may actually exhibit a greater detonation danger when stored in a container (as it surely must be in an MBT). Engineers are addressing the problem by considering propellent bladders or compartment baffles, but a completely satisfactory solution has yet to be found.

Another aspect that would tend to suggest the use of LP guns is that the Army is currently moving forward with an LP howitzer program. If LP howitzers become standard issue, then the logistical advantage of using the exact same propellent for the MBT would be undisputed. As the development program for LP howitzers continues, LP gun technology should progress to a level where it becomes meaningful to predict its future availability.

In view of the risk associated with developing an LP antitank gun, an LP gun system was not included in the configuration section of this report. However, if LP guns do become available in a form similar to that predicted, they would offer several advantages for remotely turreted gun systems. It may then be possible to seriously consider a completely external gun, which would offer many integration and survivability advantages.

3. *Electromagnetic gun systems*

There are two types of electromagnetic guns: rail guns and coil guns. Both propel a projectile by means of Lorentz forces. Advantages commonly cited for EM guns over SP guns are:

- Increased lethality
- Increased range
- Higher rate of fire
- Improved accuracy
- Reduced logistics need
- Improved survivability
- Easier combat vehicle integration

The advantages relating to single shot enhancements such as increased lethality and accuracy stem primarily from the higher projectile velocities projected for EM guns.

EM guns are in an early stage of development, and none of the above cited advantages has been experimentally proven from a system standpoint. For example, increased lethality from higher velocities seems to require a segmented rod (a long rod penetrator chopped into segments separated by light spacers). It has been shown that segmented rods continue to penetrate deeper into RHA as velocity increases, beyond the velocity threshold where continuous rods penetrate no further. However, it has not been shown how the segmented rod phenomena may be translated into a useful projectile even with a gun, such as an EM gun, capable of providing a very high velocity. Practical engineering difficulties intrude. For example, problems such as the growth in round parasitic weight at higher velocities and the increase in round length due to segmentation have not been sufficiently addressed.

For EM gun systems, sufficient electrical energy for each shot must either be stored or generated as needed. For an electrical system with a nominal efficiency of 33 percent that launches a 20 MJ projectile, roughly 60 MJ must be developed per shot. Therefore, a power generating capacity of 6 MW (8000 hp) is needed for a duty cycle of six shots per minute. This power level could be provided by a large gas turbine, such as the Allison 571k, but it would exact a high toll in system weight and volume.

The energy provided by a turbine must then be converted into electrical energy. A very-high-power device such as a compulsator, a medium-power alternator, or a relatively low-power generator might be used.

With the compulsator, the electrical pulse is formed in the proper shape for consequent rail gun use. The alternator must funnel its energy into an inductor for further pulse forming, and the generator may be used to charge up a capacitor bank which forms the required electrical energy pulse.

The energy from the electrical conversion system may then be funneled into a rail or coil gun.

The simplest rail gun consists of two conducting rails held rigidly in parallel by a supporting structure. The current flows through one rail into an armature at the rear of a projectile and back through the second rail to complete the circuit. Most of the inefficiency in the system occurs in the rails, and they must therefore be cooled. The rails are also subjected to high-friction and high-temperature erosion and must be protectively clad by a material such as molybdenum.

There are two general types of coil guns: the expanding wave and the traveling wave. The traveling wave has the potential of being more efficient than the expanding wave and receives the most attention as an antitank gun candidate. The brush commutated traveling wave gun is often cited as being the more practical system, although no coil gun system yet appears possible from a practical systems point of view.

Currently, there are development programs for three systems: a compulsator driving a rail gun with a solid armature, an alternator/inductor powering a brush commutating coil gun, and a generator/capacitor propelling a rail gun with a plasma armature. The near-term goal for these systems is to produce a gun system capable of firing three shots per minute at muzzle energies similar to the M256. The maximum system weight has been set at 20,000 kg.

The electrical energy producing equipment of the above three systems under development were projected to have energy densities of approximately 3.5 kJ/kg by the year 1989. If one further projects that a power density nearly five times this may be generated in the future, then future electrical energy conversion systems may have a specific energy of roughly 18 kJ/kg.

Since 60 MJ are projected to be required per shot, the electrical conversion machinery may be optimistically projected to weigh in the neighborhood of 6.6 tons (6 tonnes) while occupying 4 cubic meters of volume. Other system components such as the gun, autoloader, the gun cooling system, and gun fuel increase the overall system weight significantly.

Placing the above postulated EM gun system into a future two-man vehicle with sufficient armor to meet the projected threat produces an MBT weighing over 90 tons and with a much larger projected area than the M1, as shown in Fig. 17. Since this vehicle would be much too heavy and too large to be practical, it was decided not to incorporate EM gun systems into detailed configuration studies.

4. Electrothermal gun systems

Electrothermal guns convert electrical energy into projectile kinetic energy via a working fluid. They were not evaluated in detail in this study, but a comprehensive review of ET gun technology and its promise for future antitank systems was recently published by the Jet

EM gun conceptual vehicle (3.9 sq m above turret line, 10.4 sq m total)
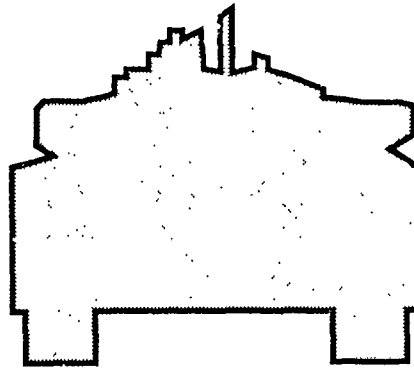
M1A1 (2.3 sq m above turret line, 6.7 sq m total)
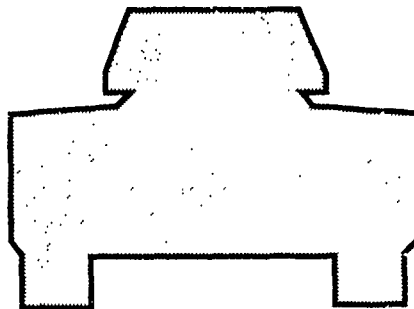
Reduced crew vehicle with conventional gun
(1.2 sq m above turret line, 4.9 m total)

Fig. 17—Frontal silhouette comparison

Propulsion Laboratory.[6] The extra conversion step required of ET guns, from electrical energy to mechanical energy, makes the technology fundamentally less efficient than EM guns. Therefore, since we have already concluded that the power generation requirements for an EM gun preclude its use an an antitank weapon, the increased power requirements for an ET gun would make it appear even less suitable.

Another gun system, often classed as a type of ET gun, is the combustion augmented plasma (CAP) gun. In some ways, the CAP gun is really more of a variety of LP gun than ET. The "propellent" in this case is usually inert until chemically initiated by an extremely hot plasma which itself is initiated by a powerful electric current. CAP guns may receive anywhere from 10 to 90 percent of their propulsive energy through chemical reaction, although for the reasons cited above, one would expect that the more practical guns would generate as much energy as possible in the combustion phase.

CAP guns represent a relatively new technology. At the time of this study, little experimental data existed in the velocity and mass range of interest. Therefore, even though the technology appears quite interesting, we concluded that it is too immature to be considered as a near-term option.

FIRE CONTROL

Regardless of the type of gun, autoloader, and ammunition storage used, a sophisticated fire control system will be needed for laying on and engaging targets. Typically, the fire control system consists of sensors, stabilization servos, and turret and gun motors (sometimes referred to as the gun drive and ballistic computer). The sensor system detects targets, determines environmental conditions (temperature, wind), and inputs vehicle state (speed, slope, system outages). For effective targeting of a 2-m target at four kilometers, the total system error (boresighting, stabilization, windage calculations, etc.) must be less than 0.2 mrad. The fire control system must also be able to track multiple targets and arrive at fire control solutions in no more than 2 to 3 sec. Finally, the turret motors must be fast enough to engage maneuvering low-flying helicopters. This requires traverse speeds on the order of 60 deg/sec and elevation accelerations of 3.5–4 mils/sec^2.[7] At the same time, smooth, minimum speed slewing is important. A maximum firing elevation of 20 deg is said to be sufficient against helicopters, and proximity-fuzed rounds may be needed.[8] Turret traverse and elevation of the main gun can be accomplished either through conventional hydraulic servos or electro-mechanical servos. The electric systems have become the preferred systems in size, cost, noise, maintenance, and safety.[9] Additional details on the makeup and performance of the sensor systems and electronics are found in the Sensor Package and Electronics sections.

---

[6]James H. Kelly et al., *Gun Propulsion: Emerging Army Technologies*, Jet Propulsion Laboratory, JPL D-3294, August 1986.

[7]Jacques Lanaerts, "Design Criteria for AIFV Turrets," *Military Technology*, Vol. 3, 1988, pp. 16–24.

[8]Robing Fletcher, "Tank Guns Against the Attack Helicopter," *International Defense Review*, No. 6, 1988, pp. 637–640.

[9]*Jane's Avionics*, Electro-Optics section, Jane's Publishing, New York, 1987–1988.

Electric turret drives and elevation motors were chosen for the reasons listed below:

- Improved survivability by eliminating hydraulic lines in the turret
- Reduced volume by reducing line and reservoir requirements
- Reduced weight
- Increased tracking accuracy

It is estimated that the turret drive will require 30 N-m (newton-meter) of torque and the elevation drive 13 N-m. We expect the turret drive to weigh approximately 50 kg, with a diameter of 210 mm and a length of 475 mm. The elevation drive mass would then be 25 kg, 160 mm in diameter, and 360 mm in length.[10]

MISSILE SYSTEMS

Light armored fighting vehicles outfitted for the antitank role usually employ antitank guided missiles (ATGMs) as their primary weapon system. Two reasons support the choice of missiles. First, light vehicles are not armored to the same degree as MBTs. They rely upon tactics to avoid direct confrontations. A tactical advantage provided by missiles is that they are much more accurate than guns at long range, generally beyond 2 km. Therefore, when employed in a defensive role or in an overwatching offensive role, light tanks could strive to remain out of range of the opposing MBTs while remaining an effective tank killer. Second, large caliber guns generate a large recoil force which light vehicles have difficulty in absorbing. The even larger guns that seem needed in the future will be a challenge to place on an MBT, much less a light tank. Therefore, the missile will continue to be a strong candidate for future light tank configurations.

Past practice has been to employ ATGMs with a command to line of sight (CLOS) guidance and a shaped charge warhead. This architecture has been widely adopted throughout the world on systems such as the TOW series, MILAN, and most Soviet ATGM missiles. Until recently, the ATGM was viewed by many as the largest threat to MBTs on the modern battlefield, largely because of the effectiveness of relatively simple ATGMs in the 1973 Yom Kippur War.

However, several problems have been endemic for ATGMs, and recent armor developments have brought their future effectiveness into serious doubt. A longstanding problem is that ATGMs travel relatively slowly, typically 200 m/sec compared with the 1600+ m/sec of high-velocity guns. They therefore take a long time to reach the target, and the gunner must be in a position to have his target in view the entire time. During this time, the gunner is not only exposed, he is prevented from searching for or engaging other targets. Therefore, the rate of fire for ATGM systems can be very slow. A more recent problem for ATGM systems is the advent of special and reactive armors. Such armors severely disrupt the performance of shaped charge warheads, and do so while adding relatively little armor mass to the vehicle they are protecting.

It may be possible to overcome these problems with technological improvements to shaped charge warheads and missile guidance schemes. For example, some ATGMs now em-

---

[10]Interview with General Dynamics Land Systems staff, 1988.

ploy two warheads, one to get through the reactive armor applique and the other to perforate the main armor. However, it appears that the predominance of ATGMs as tank killers is currently in question.

A more robust solution, one harder to countermeasure, would be to employ missiles that rely upon a long rod penetrator traveling at hypervelocities rather than slow-flying missiles dependent upon chemical energy warheads. One such missile, the hypervelocity missile (HVM), is being developed by LTV, Inc., under contract to the U.S. Army.

The current HVM program follows initial efforts begun in 1968. The guidance system and missile size are considerably different from those projected at that time. The new system employs a single-grain boost-sustain motor. The target is tracked with a dedicated FLIR (forward looking infrared) mounted on the vehicle. The FLIR and missile communicate via a pulsed laser. The missile is currently 2.3 m long, and 162 mm in diameter and weighs 77 kg.

The HVM is configured with aft stabilizing fins and a forward attitude control module. The control module consists of an array of small thrusters spaced radially around the missile. Firing these thrusters varies the angle of attack, providing maneuver corrections to a desired trajectory. The missile contains no moving mechanical parts except for the pop-out fins and a roll reference gyro, and it retains the expended rocket motor throughout the flight. This configuration results in a relatively high drag, so a sustainer thrust element is included in the propellent grain.

A desired trajectory off the line of sight is computed before launch, and the missile flies an approximation of the desired trajectory as computed by an on-board processor. A FLIR located at the launch site tracks both the missile and the target to establish deviations from the desired flight path. A CO_2 laser at the launch site projects a coded format from which the missile can read errors from the desired trajectory and compute and implement corrective maneuvers.

Test firings of the HVM began in December 1988 and are continuing. In general, none of the firings has been a total success, but each firing to date has demonstrated some important aspect of the system. The HVM was considered far enough along in development to warrant closer examination of its integration characteristics, which may be seen in a later section.

MOBILITY SYSTEMS

To be effective, an MBT must be tactically mobile over a variety of terrains. Mobility may be defined by parameters such as engine power, ground pressure, roadwheel travel, maximum obstacle height clearance, and so on.

It is critical that the MBT remain as light as possible because the most powerful engine and responsive suspension system will not negate the adverse effects of extreme weight. After MBT weight minimization, the most important mobility design consideration is the drive train—the engine and transmission. An overview of MBT engines and transmissions is presented here, followed by detailed reviews of the Advanced Integrated Propulsion System (AIPS) and electric transmissions.

The suspension system is also vitally important, especially for cross-country mobility. Suspension system components include tracks, roadwheels, a hydraulic pump and reservoir, sprockets, idlers, and brakes.

The MBT draws power from the primary mover for various tasks. It often provides power for electronics; nuclear, biological, chemical (NBC) air; turret and gun drives; crew and electronics environmental control; and battery recharges. These secondary tasks may be powered by an auxiliary power unit (APU). Several candidate APUs are mentioned in this section.

Drive Train Requirements

The drive train consists of the engine, transmission and control system. The requirements outlined here stem from the Advanced Integrated Propulsion System program. They may be divided into several categories: power, speed profile, fuel consumption, size, mass, cooling, braking, and steering. The requirements discussed here are by no means complete, but give the reader a general understanding of the tradeoffs to be considered when choosing a drive system. A summary of AIPS requirements is shown in Table 3.

Although the requirement for a continuous tractive effort (TE) is listed at 70 percent of gross vehicle weight (GVW), required TE is a function of road speed. In general, the necessary torque to maintain a straight path decreases as speed increases and grade decreases, and the stall TE is approximately 100 percent of gross vehicle weight for a 60-ton MBT. Another important requirement is minimizing fuel consumption over an average battle-day. During the course of a 24-hour battle, the engine will be stopped and started several times, run at full power and at idle, and provide "housekeeping" power, as shown in Table 4. The current AGT 1500 with the Allison X1100 transmission requires nearly 500 gallons of fuel to

Table 3

SUMMARY OF AIPS REQUIREMENTS

Parameter	Condition	Requirement
Sprocket power	30°C/150 m	1050 hp
	49°C/150 m	892 hp
	20°C/1800 m	787 hp
Tractive effort	Maximum	1.2 GVW
	Continuous	0.7 GVW
Vehicle speed	Forward	75 km/hr
	Reverse	30 km/hr
Acceleration	To 20 mph	7 sec
Multifuel		DF-1,-2,-A, gasoline
Cooling margin	Mission points:	
	0.7 TE/weight	30%
	Downhill braking	30%
	75 km/hr	30%
Air filtration		200 hr @ zero visibility

SOURCE: Interviews with U.S. Army Tank Automotive Command and AIPS contractors.

NOTES: GVW: gross vehicle weight; TE: tractive effort. Sprocket power shown for ambient temperature and altitude. Downhill braking on 15 percent slope at 16 mph.

Table 4

BATTLE-DAY (24-HOUR) POWER/TIME DELINEATION

MPH	Mission Condition	Shaft HP	Total HP	Time (hr)
0	Idle	18	34	0.3
0	Idle	233	248	0.9
0	Electric power generation	18	34	0.5
25	Secondary roads	657	672	3.4
17	Cross-country	830	846	3.3
0	Silent watch	19	35	1.5
0	Starting[a]	18	34	0.5

[a]Thirty minutes at idle for battery recharge.

meet battle-day requirements.[11] A future drive train should require roughly half of this fuel quantity, or 250 gallons. However, while only one battle-day of fuel is required, two battle-days are desired, with much of that under heavy armor protection.

The most important AIPS requirement is the space limitation; the entire drive train with peripheral automotive components should not occupy more than 194 cubic feet of space. The space must be contained within the dimensions shown in Fig. 18. A secondary requirement is that the powerpack be somewhat lighter than the 6400 kg for the current M1-A1 power pack.[12]

M1-A1 ----

AIPS ——

Measurements in cubic ft.
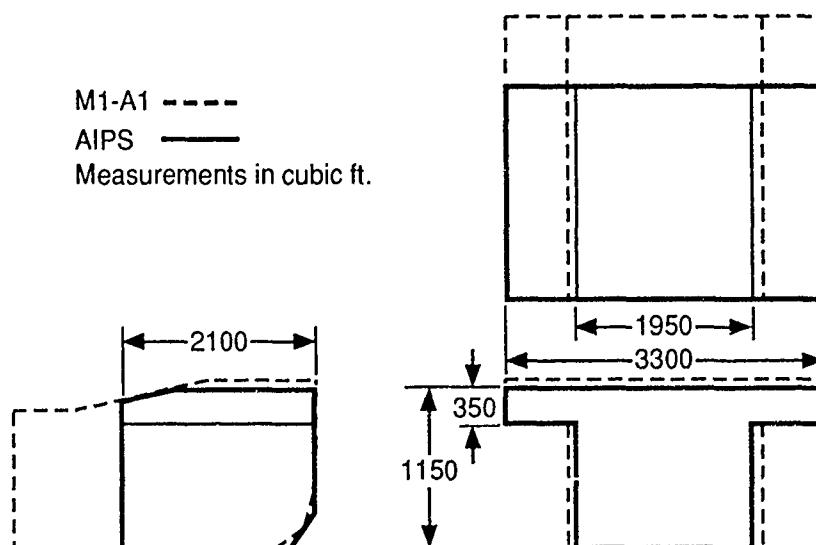
Fig. 18—AIPS dimension requirements

[11]Chrysler Defense, Inc., *Characteristics and Description Book, M1E1 Tank*, TA-80-01105-002, October 1981, pp. 2–16.

[12]U.S. Army TACOM, *M1A1 Tank System Weights*, AMCPM-CGM-SA, May 1987.

Overview of Engine/Transmission Development. The traditional measure of MBT mobility is the power-to-weight ratio, also known as specific output. The specific output is arrived at by dividing the maximum engine output power by the weight of the vehicle. This measure is not entirely satisfactory for a number of reasons. First, the efficiency of the transmission and final drive is not taken into account, nor is the power drain from secondary components such as electronics or the NBC system. Second, cross-country mobility is a function more of suspension than engine power. Third, as tank weights continue to increase, overall mobility must eventually decrease regardless of the specific power.

Over the years, impressive reductions in both engine mass and volume have taken place. In the last 30 years, weight specific power has increased by 400 percent and volume specific power by 600 percent.[13] Advancements have allowed MBT specific power to be increased in spite of the weight growth of the main battle tank over that same period from 35 tons to 65 tons. Prior to 1970, most Western MBTs had a specific power of roughly 10 kW/t; today the nominal MBT exhibits double that figure.[14]

Tank transmissions are fairly complex since they must steer and brake the vehicle. The M1-A1 transmission, the Allison X1100-3B, has two power trains. The primary power train mechanically transfers power through a series of gears, clutches, and shafts to the main sprocket. It provides power while the vehicle is moving forward or backward in a straight line.

The secondary system, often referred to as the torque converter, is usually a hydrostatic system consisting of a series of hydrodynamic pumps, valves, and motors. The secondary system provides power for turns, while shifting between primary gears, and for very low speed operation. For most transmissions, less secondary system use results in higher transfer efficiency. Some of the more modern MBT transmissions, such as those projected for the AIPS program, use a double-clutching system that allows full lockup past first gear.

In the West, MBT engines and transmissions are under development in the United States, Germany, France, and the United Kingdom. In the United States, the main programs are AIPS and the transverse-mounted AGT 1500. In addition, several studies have examined electric drives, and the John Deere rotary diesel has been posited as an MBT primary mover. In France, the unfolding LeClerc is driving the development of the Poyaud V8X diesel and SESM's ESM 500 transmission. In Germany, MTU is cooperating with General Motors in developing the MTU 883 integrated diesel. The British are working on a 1200-hp diesel, the Perkins Condor CV12, with upgrade potential to 1500 hp. Several of these systems are discussed below.

The Advanced Integrated Propulsion System. AIPS is a U.S. Army program to develop drive system demonstrators for a future MBT or MBT upgrade. Two features distinguish the program. First, both turbine and diesel power packs are being developed simultaneously. Second, each power pack is fully integrated with transmission, starter, battery pack, fuel, and auxiliary automotives. A team led by General Electric is developing the turbine AIPS, and Cummins is leading the diesel AIPS team.

The two prime contractors were chosen from the six contractors who participated in the Phase I concept development. The four contractors not participating in the Phase II hard-

---

[13]Rolf Hilmes, "Battle Tank Mobility," *International Defense Review.* Vol. 9, Battle Tank Supplement, 1985, p. 22.

[14]Hilmes, p. 23.

ware development are Garrett, Teledyne Continental, Williams, and Allison, although Allison is developing the transmission for both winning teams. Phase I began in August 1982 with the downselect completed and Phase II initiated in July 1984.[15]

In Phase II, both Cummins and GE are contracted to provide the Tank-Automotive Command (TACOM) with two fully operational power packs for testing in a mock engine compartment at TACOM facilities. Phase II funding has been allocated for the entire program, which is scheduled to be completed in June 1990.[16] The AIPS schedule coincides with current schedules for the Integrated Technology Demonstrator (ITD), the M1-A1 Block III upgrade program, and the AFV(H) schedule. AIPS is scheduled to be used in both the ITD and in the Block III upgrade.[17]

GE has designated their AIPS developmental package as the LV100. The main components of this package are the turbine core, the transmission (includes braking system), the recuperator, the cooling system, the infrared (IR) shielding system, the fuel system, and the air-inlet filter. Each AIPS contractor is required to designate a second-source supplier, and Textron Lycoming (formerly Avco Lycoming) was chosen as GE's second-source contractor in December 1987.

Much of the technology in the high-pressure turbine stems from the GE T700 engine. For the low-pressure turbine, the MTU 7042 provides some of the technology base.

A portion of the technical challenge in fielding a turbine resides in reducing its fuel consumption over a range of output torques and speeds. Several of the enabling technologies proposed by GE include variable camber compressor blades, mono crystal turbine blades, and cooled airblast injectors. In general, classic turbine design methodology for increased efficiency is applied: operate at the highest possible temperatures, vary air intake with power demand, and recuperate as much heat as possible.[18] GE claims that the fully integrated LV100 will consume 276 gallons of fuel over a 24-hour battle-day (30°C/150 m), which is 45 percent less than the current AGT 1500. GE hopes to decrease fuel consumption across the power range, but most reductions will come at low-power output. Increased engine efficiency at low-power output is critical to reduce turbine fuel consumption since, as one can see in Table 5, much of the battle-day is spent at relatively low-power outputs.

GE will likely succeed in producing a turbine more efficient and compact than the current AGT 1500 since the AGT 1500 represents 15-year-old turbine technology. However, since the LV100 has yet to be tested in an operational system, it is difficult to predict how close GE will come to its fuel consumption goal.

GE projects that its system will occupy less volume than that required by the AIPS contract. The projected LV100 will allow a certain amount of leeway for vehicle integration since the propulsion system could be shortened, with components relocated in the sponsons. The LV100 has a forward compartment, currently containing fuel, which could be located elsewhere in the vehicle. The final weight of the wet power pack with IR suppression and auxiliary automotive equipment is projected to be under 5.5 tons.

---

[15] Interview with Charles J. Raffa, U.S. Army TACOM, January 1988.

[16] Rupert Pengelley, "AFV Propulsion: Americans Advocate Integration," *International Defense Reviews*, Vol. 5, 1988, p. 542.

[17] Interview with Mr. J. B. Gilvydis, U.S. Army TACOM, September 1988.

[18] Interview with Mr. L. Kutz, Manager, Propulsion Systems Design and Integration, General Electric Company, April. 1988.

Cummins is developing the diesel version of the AIPS; it is designated as the XAP-1000, with the engine designated as the XAV-28. Holset Engineering is supplying the turbochargers. Allison is again providing the transmission, and Garrett is developing the IR suppression system. Cummins is integrating all components at its Colombus, Ohio, plant.

The XAV-28 is a four-stroke V-12 that features high-pressure turbocharging and low heat rejection. The V-12 is at a relatively high angle—60 deg—which reduces engine width. The cylinder bore is 150 mm with a stroke of 130 mm. The engine displaces 27.5 liters and has a dry weight of 1891 kg. Cummins estimates that the XAP-1000 will consume 225 gallons of fuel per battle-day.

While the primary challenge for the turbine is to reduce fuel consumption, the main technical advancement required for the diesel AIPS is to minimize size. Cummins is approaching size minimization through improved packaging and advanced technology. The primary methods for decreasing size are increasing operating temperature, turbocharging, increasing fuel injection pressure, and decreasing engine heat rejection.

High-temperature operation is enabled largely through the use of a synthetic oil and oil cooling (no water). When combined with low heat rejection, the high oil temperatures increase heat exchanger efficiency, thereby decreasing aftercooler size.

The Holset turbocharger features variable vane geometry, which allows a 3.8 pressure ratio increase in a single stage. High fuel injection pressures, over 20 ksi, are created at the rocker arm before being introduced to the cylinder by the electronically controlled injector. Creating the pressure at the cylinder head precludes the need for high-pressure fuel lines.

The transmission being developed by Allison has seven forward speeds and two reverse. The torque converter locks up past first gear, and a hydrostatic system is employed for steering.

One of the advantages often cited by Cummins of a diesel AIPS is that diesels are easier to modify, thus allowing Cummins to offer a family of diesel AIPS if required. They range from 480 hp (561 cu in.) to 1450 hp (1682 cu in.).

Cummins also claims that the XAP-1000 will be significantly smaller than AIPS requires, although GE claims that the LV100 will be smaller still. The XAP-1000 is projected to occupy 175 ft³, the LV100 170 ft³ with one battle-day of fuel. This volume advantage is reversed, however, when two battle-days are carried. In that case, the XAP-1000 will occupy 205.1 ft³ and the LV100 206.8 ft³, although the difference in either case is so small as to be inconsequential.

The LV100 will require more filtered air than the XAP-1000, but the diesel will require more air overall. Air intake is critical since it determines the amount of necessary grille space, and grilles can be difficult to protect and integrate. The total grille space for the diesel is projected to be double that for the turbine, or roughly 20 ft².

Grilles weigh roughly three times more than armor plate for equivalent protection. Therefore, if grilles are taken into account, the final diesel engine mass is projected to be roughly 1.7 tons heavier than the turbine with one battle-day of fuel for an XAP-100 equivalent weight of 7.2 tons.

Other U.S. Tank Engine Programs. Two other engines of interest for tank propulsion are the transverse-mounted engine propulsion system (TMEPS) and the John Deere rotary diesel. The rotary is not being developed specifically as a tank engine, but its relatively small size makes it an interesting candidate for future developments.

The TMEPS program was awarded to General Dynamics Land Systems (GDLS) in October of 1986. Textron Lycoming is modifying the AGT 1500 turbine and Allison the XT1100-3B transmission. The goal of the program is to mount the engine transversely in the engine compartment adjacent to the transmission. This should free approximately 40 inches of space within the engine compartment, which is 1.27 m³, for other uses. The revised power pack would be 2.125 m long, 1.98 m wide, and 1.175 m high.[19]

GDLS is also pursuing efficiency improvements and performance upgrades. GDLS estimates that the AGT 1500 TME would consume 20 percent less fuel in a battle-day with slightly more power being delivered to the sprocket.

John Deere is developing a family of diesel rotary engines that may provide either primary or auxiliary power. The TMEPS program proposes to use a stratified charge omnivorous rotary engine (SCORE), Series 70, as an 80-hp auxiliary power unit (APU) that could also power the NBC kit. The Series 70 SCORE is receiving serious attention for a number of military applications. The Air Force, for example, is considering a tandem motor configuration for a 120-kW generator set.

The SCORE family of interest to tank designers is the Series 580. In this series, from one to six rotors may be linked to provide a power range of 375 to 2260 hp. John Deere claims that, with further development, the power rating for the Series 580 may be nearly doubled. Such a power upgrading would result in a remarkably compact and light diesel.

The SCORE Series 580 is under consideration for a number of military applications including shipboard generator and primary mover for the Advanced Amphibious Assault Vehicle (AAAV). Versions of the Series 170 have also been studied for possible armored vehicle applications.

For MBT applications, the Series 580 engines of interest are the four-rotor 4231R and the two-rotor 2116R. The 4231R is currently rated at 1500 bhp, with a "growth rating" of 3000 bhp. John Deere states that the higher power rating would require three to five years of development before a prototype could be demonstrated. They also claim that the growth, which would come from additional turbocharging and intercooling, would add little to engine size.[20]

The four rotors of the 4231R displace 14 liters. The engine occupies 1.15 m³ of space and weighs 1020 kg. The 2116R, growth rated at 1500 bhp, would displace 7 liters. It would weigh 725 kg with a volume of 0.85 m³. For the Series 170, only the growth-rated Model 6102R is of interest. This six-rotor diesel would displace 6.3 liters in generating 1500 bhp. The engine would occupy 0.54 m³ and weigh 1130 kg.

Although engine specifications for the SCORE engines appear promising, it is difficult to compare rotary diesel performance with AIPS and TMEPS since no integration study for SCORE has been performed to date. However, if one assumes that an integrated package would be directly influenced by the engine size and mass, then a rough estimate of SCORE potential for MBT applications may be formulated.

Because the diesel AIPS incorporates various components within the engine, such as core cooling, it was assumed that the SCORE could more appropriately be used to replace the turbine and recuperator in an integrated package. The LV100 turbine and recuperator

[19]Pengelley, p. 543.

[20]SCORE Rotary Engine Physical and Performance Data, John Deere Technologies International, Woodridge, New Jersey, January 1988, p. II.2.

weigh 910 kg and occupy 1.01 m^3 of volume. Therefore, replacing the turbine with the growth-rated 2116R could conceivably decrease AIPS engine weight by 20 percent and decrease volume by 16 percent. This comparison is crude, and several significant differences between the systems would need to be examined before any real conclusions may be made. For example, the 2116R would probably be more fuel efficient, and require less filtered air and more induction air than the LV100. Also, the growth-rated version of the 2116A has yet to be demonstrated. However, if the rotary diesels ever demonstrate such high power density, they would make an attractive option for MBT drives.

Electric Transmission Technology

Studies examining electric drive (ED) for tracked armored vehicle applications have been conducted over the past six years by TACOM (1987), AFC (GDLS/FMC, 1987), TACOM (AIPS study, 1984), and the Marine Corps (1982).

The TACOM studies recommended that ED was not sufficiently mature to warrant a large development program.[21] The Marine Corps initially recommended ED for land mobility, but has recently decided against ED for its Advanced Amphibious Assault Vehicle.[22] Only the GDLS/FMC team has recommended that ED be pursued for the next generation of armored vehicles.

Various test bed programs have been used in gathering data on ED systems. GDLS operates a 15-ton 6 × 6 called the Electric Vehicle Test Bed (EVTB), and FMC uses a converted M113 chassis to house its test bed. The Marine Corps was at one time also operating a tracked test bed, but it has since terminated the program.

Proponents of ED claim the following advantages for armored vehicle applications:

- Configuration flexibility
- Lower volume and weight
- Fewer moving parts (simpler, quieter, and less expensive)
- Greater growth potential
- Compatible with EM and ET guns

Past difficulties with ED systems include:

- High volume and weight
- Low efficiency (large cooling requirements, large thermal signature, and more primary power)
- High-torque/high-speed incompatibility (requires oversized motors or two-speed final drives)
- Immature technology base

The design gains stemming from configuration flexibility have not been adequately documented to date. It has been argued that the flexibility would be well suited for front engine

---

[21]Interview with T. Herrera, U.S. Army TACOM, 1988.
[22]Interview with M. Gallager, U.S. Marine Corps David Taylor Laboratory, 1988.

designs. However, since AIPS contractors (among others) claim the ability to meet front engine compartment restrictions, the added flexibility of ED may not be required in this application.

Another area where greater flexibility may be of interest is in relocating the turret and ammunition compartment. Currently, the ammunition compartment for a rear engine MBT is in the center of the vehicle, which is the aim point for any shots between the 45 deg and 135 deg azimuths. Moving the ammunition off the aim point would increase the survivability of the vehicle. Of course, a more direct solution to the problem of ammunition vulnerability is simply to make the ammunition less vulnerable, but this would also require a substantial development program.

Increased flexibility could be used to enhance survivability through redundancy. For example, ED could allow two engines, or the roadwheels themselves could be driven in an emergency. However, the value of redundancy has never been adequately addressed.

The basis for the claim of lower volume and weight will be partially addressed in this section, although we note that one of the historical problems with ED has been that it is both much heavier and more voluminous than mechanical transmissions.

Another potential advantage—compatibility with ET and EM guns—would, of course, be applicable only if electrically driven guns were pursued for MBT use. If they are, more research must be conducted regarding the compatibility of electric gun and drive components. Since guns tend to require short bursts of extremely high power and drives sustained power at varying load levels, one may expect compatibility challenges. In any case, neither electric guns nor electric drives have been developed to a point where symbiotic tradeoffs between the two systems may be accurately predicted.

Of the past problems associated with electric drives, those involving the size, efficiency, and power rating are the most challenging. Some of the technologies being studied or proposed for overcoming these challenges are discussed below.

The major subsystems in an ED are:

- Primary mover
- Generator
- Power control unit
- Traction motor
- Final drive
- Electronic control unit

The generator and motor may be powered by either AC or DC current. The power control unit (PCU) could be a rectifier/invertor or a bank of silicon controlled rectifier (SCR) switches, and the electronic control unit (ECU) would normally be computer driven, although simple feedback loops may also be incorporated. The final drive could be either one or multiple speeds.

A sample ED schematic is shown in Fig. 19. The AC traction motors are driven by an AC generator that has been properly adjusted by a PCU. There are numerous other possible configurations. A DC circuit could be powered by a DC homopolar generator, or AC power could be rectified to power DC motors. An ED could also be integrated with a mechanical drive. With the possible exception of the primary mover, none of the components required for
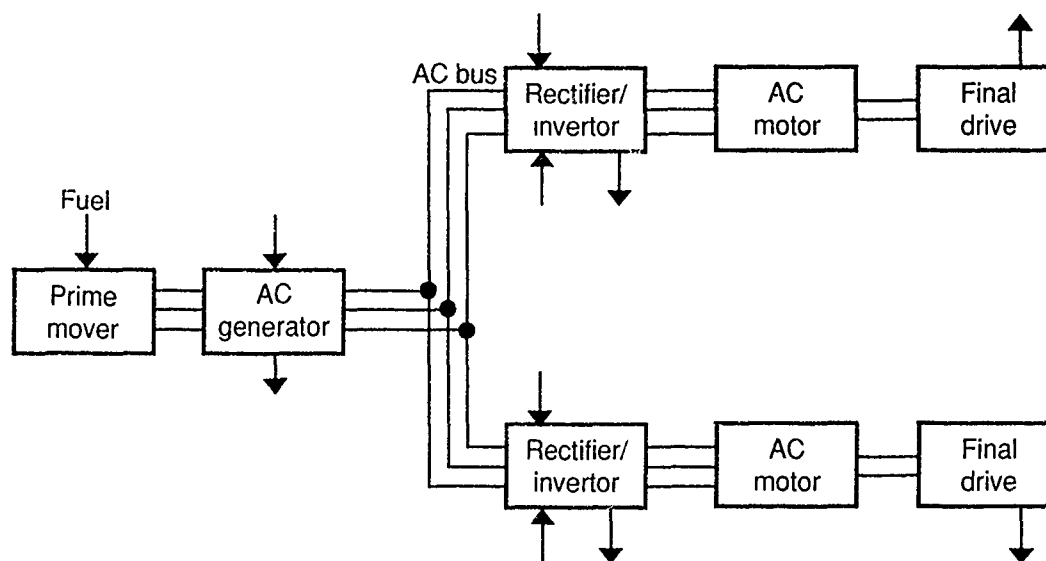
Fig. 19—Example electric drive schematic

an effective ED system is currently in full production, although many are in the prototype stage of development.

Garrett, Westinghouse, and Unique Mobility are among the many contractors developing light high-power AC generators. Garrett and Westinghouse are each developing systems rated at a nominal 750 kW. Each system is projected to weigh approximately 120 kg, and Garrett estimates that their system would occupy roughly 1 cubic foot, which is half the volume predicted for the Westinghouse system. The maximum power rating for the Westinghouse system is projected to be 860 kW for a five-minute duration, whereas the Garrett system is not rated for above-continuous-power settings. Garrett predicts that their system will be slightly more efficient than the Westinghouse system, with 94 percent peak efficiency versus 93 percent for Westinghouse. A complete comparison between the two systems and others may be found in the literature.[23]

The current from the generator (or generators) is subsequently processed by the PCU. In one type of PCU, the AC signal is rectified into a DC signal, which is then reformed into an AC signal of the proper frequency and phase. In this circuit, a thyristor bridge is used to rectify the AC signal, and a separate but identical bridge then reconstitutes the signal. Since the circuit is symmetrical, the power flow may be bidirectional, which would be required while braking or steering.

The most challenging aspect of the PCU is that the solid state switches must be small, lightweight, reliable, and capable of quickly switching high currents. Gate Turn Off (GTO) thyristors have normally filled this role, but they are too bulky for practical use on an MBT, with designs over 6 m³ in volume and 3800 kg in mass; therefore, newer technologies must be

---

[23]See, for example, a report funded by TACOM: G. M. Harper, and J. R. Underwood, *Final Electric Drive Study Technology Survey Report*, GDLS, JU-84-04057-001, January 1985, pp. 4.1-4.12.

developed.[24] At present, metal oxide silicon (MOS) may be the most promising for reducing PCU size. For example, Garrett proposes to reduce PCU size to roughly 0.03 m^3 and mass to 450 kg in the near term.

Once the AC signal is properly formed, it is fed into the traction motor. Again, this technology must be more thoroughly developed for MBT applications. Two manufacturers researching potential traction motors are Garrett and Unique Mobility.

Garrett is developing a permanent magnet (PM) synchronous motor rated at 483 hp with a 30-sec overload capacity twice that. If the motor were linearly scaled to 600 hp, it would weigh approximately 350 kg and occupy 0.07 m^3 of space. However, since motor power levels rapidly decrease below 4600 rpm (18,500 rpm max), either a two-speed final drive would be required for low-speed/high-torque operation, or the engines would need to be oversized to accommodate reduced power availability at low speeds.

The Unique Mobility (UM) motor is also of the PM synchronous type, but it features an external rotor. This feature holds forth the possibility of locating the final drive within the motor housing, thus saving space. Another interesting potential feature of the UM motor is that it may be dynamically reconfigured to, in effect, electrically shift the final drive, allowing continuous power output over a very broad rotational speed range. This would presumably allow a single-speed final drive. However, the UM motor is in the early development stage, and may be considered a high-risk development item.

One of the difficulties associated with ED is that most of the motors run most efficiently at very high rotational speeds. Since maximum sprocket speeds are typically around 700 rpm, rotational speeds must be stepped down by well over an order of magnitude. In stepping down from 10,000 rpm to 700 rpm, Marine Corps designs suffered significant windage losses. Their double planetary gearing system, which also served as the two-speed final drive, was approximately 70 percent efficient.[25]

Suspension System Tradeoffs and Technology

The most important system in cross-country mobility, other than the overall requirement of minimizing MBT weight, is the suspension system. This system consists of the suspension units, shocks, trailing arms, roadwheels, idlers, and tracks.

Parameters that, to some extent, govern cross-country mobility are power-to-weight ratio, ground clearance, roadwheel travel, ground pressure, center of gravity, vehicle length-to-width ratio, maximum step height, and maximum trench width. Many of these parameters are "system" parameters, and, indeed, mobility is largely a system problem.

The primary requirement for the choice of components represented in this section is that they be realistic and practical, but not necessarily the most advanced component of their type. For example, only conventional tracks were considered, although significant weight savings would accrue if looped tracks were developed.

---

[24]Volume and mass are based on 1200 hp at sprocket powered by PCU similar to Westinghouse production model: SCR converter, LC filter, GTO inverter, 5.55 hp/ft^3, 0.142 hp/lb.

[25]Interview with M. Gallagar, David Taylor Laboratory, 1 February 1988.

The two tracks considered are shown in Table 5. One set was developed by FMC and is similar to that currently on the M1-A1; the other set was developed by Diehl. The FMC set was chosen in this case for the simple reason that they are standard in pitch, and the AIPS drives are being designed to that pitch.

The roadwheels are similar in size to those of the M1-A1. The ground clearance was originally set at M1-A1 levels, but became slightly greater with the introduction of a hydraulic suspension set.

The Teledyne Continental rotary actuating hydropneumatic suspension unit was chosen. In addition to the suspension units, a hydropneumatic suspension system requires a hydraulic reservoir and pressure pump. In the vehicle designs, a space is designated for 50 gallons of hydraulic fluid and a pump. Area for hydraulic conduits to each wheel set is also provided. This system was chosen as a notional system that meets requirements rather than as the best system available, which it may or may not be.

A hydropneumatic system offers several capabilities other than increased responsiveness for improved cross-country mobility. For example, the system allows the MBT to kneel. That is, it may achieve a higher defilade or elevation angle when stationary. It is also conceivable that the ability to raise the front end may increase the maximum step height, if the operator has time and warning to prepare for the step crossing.

NBC System

Although the NBC (nuclear, biological, chemical) system is arguably a protection system, it is included here because it relates directly to drive train tradeoffs. The NBC system chosen in this study is being developed by Garrett Corporation. Although better systems may or may not also be under development, the Garrett system gives a reasonable notion of space and mass requirements. An overpressure NBC system with a dedicated APU was chosen for several reasons. First, for a reduced crew vehicle, the crew is faced with a large variety of tasks that require a fair amount of agility and mobility within the crew compartment. An NBC suit would greatly hamper crew function. Second, since one would not want a mobility kill to produce a crew kill in an NBC environment, a dedicated APU is placed with the NBC kit in close proximity to the crew space.

Table 5

TRACK OPTIONS

Item	FMC	Diehl
Track width	25 in.	25 in.
Track pitch	7.625 in.	7.226 in.
Roadwheel path	Rubber	Steel
Pad type	Replaceable	Replaceable
Pin diameter	1.5 in.	1.252 in.
Centerguide	Replaceable	Integral
Weight	4983 kg	5432 kg
Average track life	2091 hours	5600 hours
Average pad life	870 hours	715 hours

SENSOR PACKAGE

The sensor package for future armored vehicles is critical. The vehicle must have on-board capabilities for fighting in an obscured battlefield, against difficult-to-detect targets, without compromising the vehicle position or status. The sensors must cover the spectrum of 24-hour battle, in adverse weather, and under conditions of smoke and dust. They must be capable of both rapid, wide-area search and long-range target identification, whether the vehicle is moving or stationary. The sensors should be able to detect vehicles and aircraft at ranges exceeding 5000 meters, and be able to determine target status—moving, disabled, or firing. They must be capable of determining accurate target position information and digitally relaying that information to other neighboring vehicles.

Since they are so important, the sensors must be well-protected and redundant. Protection requires the exposed sensor package to be small, with substantial armor as well as beam weapon protection. Redundancy is necessary in all facets: sensors, stabilization, mounting, networking, signal processing, and power supply. With these requirements in mind, we surveyed what is available and what is in development.

Sensor Choices

The sensors we considered for use on the vehicle are the following:

Hard optics (telescope, vision blocks). These give excellent resolution, good color contrast, high reliability, and passive operation at low cost. They do not have night capability and provide little haze penetration.

Day TV (full color video with zoom). Resolution is almost as high as with black and white TV, but color gives better target discrimination against ground clutter. Day TV provides better haze penetration than hard optics.

Low-light-level TV (LLLTV). Fluorescent image intensification is added to black and white TV, allowing use down to starlight illumination levels. Resolution of LLLTVs, even Generation II and Generation III systems, is typically well below that of FLIR systems. However, LLLTVs are less expensive and smaller and require less power than FLIRs.

FLIR (8–12 micron). This infrared imaging sensor provides passive sensing day or night. The long wavelength HGCdTe detectors are scanned to provide a scene similar to that of TV. Differences as low as 0.2°C at the sensor can typically be discriminated. The sensor penetrates most smokes, but can be degraded by rain and fog.

FLIR (3–5 micron). This is similar to the 8–12 micron FLIR, but concentrates on emissions in higher temperature regions, such as vehicle exhaust, roadwheels, etc. The advantages are that the shorter wavelength gives higher resolution with the same optics, and the platinum silicide detectors can be made into inexpensive focal plane ar-

ray staring detectors. In combination with an 8–12 micron FLIR, a 3–5 micron unit can usually discriminate thermal decoys.

Laser radar. A long wavelength (10 micron) CO_2 laser is scanned across the target, giving information about shape and vibration. Current developmental systems are large and expensive and take many seconds to scan even a small sector. Like FLIRs, laser radar can penetrate most smokes, but because the system is active, it may alert the target or other enemy systems. Successful tests have been made in space for the Strategic Defense Initiative (SDI) program. In particular, Litton reported a successful test of a space-based CO_2 radar weighing about 20 kg.[26]

Millimeter wave (MMW) radar. This tank-mounted sensor penetrates all known smokes due to its very long (3-mm and 1-mm) wavelengths. It can be transmitted by either a normal or a phased array antenna. It provides doppler movement information and metal discrimination. However, MMW is an active sensor with limited directional accuracy.

Laser ranging. Here a pulsed Nd:YAG or CO_2 laser is used to determine target range. It can also provide chemical detection capability, and might be used to cue remote fuzing of antihelicopter rounds.

Acoustic sensing. Microphones are used to determine target sound and vibration signatures. Under good conditions, a tank can be identified to a distance of 1 km, even without line-of-sight, and can be directionally placed within as little as 2 deg. However, performance degrades rapidly with battlefield noise, rain, and foliage.

Laser/radar warning. Sensors are placed on the surface of the vehicle to alert the crew to active sensing by the enemy. The sensors are sensitive to various frequencies and attempt to match the signals to stored templates. Only imprecise directional information is obtained.

It should be evident from the above descriptions that an integrated set of sensors will be needed to cover the full range of battlefield conditions. Night sensing, for example, is best done with a combination of 3–5 and 8–12 micron FLIRs because they can see through most types of smoke and fog. LLLTV provides less resolution (except in clear starlight conditions), less range, and substantially less penetration of smoke, fog, haze, dust, and rain. However, it can be used in a low-cost back-up system that might be chassis-mounted. Clear day sensing, on the other hand, is best done with a combination of 8–12 micron FLIR, high-resolution color TV, and hard optics. In daylight conditions of mist, fog, and dust, FLIR and TV penetrate better than hard optics.

Bispectral smoke requires use of MMW radar, which also gives added capabilities for moving target indication (MTI) cueing and non-metallic decoy discrimination. Unfortunately, against ground clutter, MMW radar can usually only cue the operators to a

---

[26] Research and Technology Section, "Laser Radar," *International Defense Review*, No. 6, 1988, p. 719.

target, giving directional information for fire control once the target closes to a few hundred meters. Smoke tends to be nonhomogeneous, so the MMW can track the target (within a degree or so angular resolution with a small antenna) during completely obscured intervals, and then cue FLIR or TV sensors. Such tracking must be done judiciously, since the MMW is an active sensor.

Non-line-of-sight sensing, finally, requires use of acoustic sensors or close coordination with other units. Acoustic sensors can give general information about target type, range, direction, and activity. They are especially useful for alerting to the presence of helicopters, and they can help to discriminate decoys. Acoustic sensors can identify the type of helicopter from the beat pattern of the rotor,[27] although normally the tank must be passive and stationary, with its engine switched off.

All of these technologies should be available to some degree for near-term application. Some far-term additions would be laser radar (for high-confidence target identification), focal plane array (FPA) FLIR, and FPA MMW radar. The FPA versions should result in reduced system size and cost.

Sensor Specifications and Availability

We next describe some specific sensor components that are currently available or in near-term development. We will give near- and far-term recommendations for most items.

Video Sensors. Low-light-level TVs are needed for the chassis, and high-resolution day TVs should be mounted in the sensor masts. The following are some available systems.

> LLLTV: General Electric AN/ASQ-174 low-light-level TV with wide dynamic range, 875-line resolution, and second-generation photocathode intensifier. The system has an 8-deg field of view night sight, although other fields of view are available. The dimensions are: camera head: 3 in. diameter, 9 in. long, 3 lb; electronics: $9.5 \times 7.3 \times 6.5$ in., 10 lb. It should be able to detect a tank at 1.25 km, without zoom.

A more expensive third-generation system, using gallium arsenide photocathodes, can be specified for the far-term system. Baird, SFIM, and others produce such sensors. The dimensions are roughly the same as those of the GE system.

> High-resolution day TV: Itel mini electrooptical imaging system. This charge-coupled device (CCD) camera has a 2000×2000 pixel array and wide dynamic range. The camera head is 4 in. diameter and 7 in. long, and the associated electronics are $6 \times 6 \times 8$ in. The total system weight is 20 lb.

Wide-angle lenses may have to be fitted to these cameras for driving, as roughly a 20×40 deg field of view is required at unity magnification.

FLIRs. Two FLIRs are needed, one for each mast. In this way each crew member can scan a different area or track different targets. Only one FLIR need be the high-resolution,

[27]Robin Fletcher, "Tank Guns Against the Attack Helicopter," *International Defense Review*, No. 6, 1988, pp. 637–640.

high-cost, bulky unit such as that in the current M1. The second can be a smaller aperture mini-FLIR similar to those used in remotely piloted vehicles (RPVs) and small surveillance aircraft. For the near term, both FLIRs should be in the 8–12 micron range using HgCdTe scanning detectors.

> Main FLIR: The default is the upcoming M1 commander's independent thermal viewer (CITV) sight with 2.5 × 3.3 and 8.6 × 11.5 deg fields of view. The unit weighs roughly 80 lb (including a day sight), and occupies roughly 0.5 cu ft in the mast and 1 cu ft in the chassis. It resolves to at least 0.2°C.

> Auxiliary FLIR: The Honeywell mini-FLIR is a smaller and somewhat less sensitive unit suitable for the second mast. This unit, originally planned for the Aquila, has a single field of view (24 deg vertical and 37 deg horizontal). The sensor module is roughly 5 in. diameter and 7 in. long, while the electronics and cooling module is roughly 5 × 5 × 8 in. Together they weigh 20 lb. Multiple field of view units are also available, with very little change in size or weight. One version is 25.5 lb including gimbals and electronics, packaged in an 8.5-in. diameter ball. Ford Aeroneutronic and FLIR Systems make similar mini-FLIRs. The FLIR Systems unit comes with a built-in low-frequency stabilization unit.

For image handling from all the scanning devices, the system may use a pair of Rockwell common module digital scan converters. They allow the user to electronically zoom a portion of the display, freeze-frame a scene for inspection or to negate LOS blanking, and integrate several frames to reduce noise. Each unit is roughly 100 cu in., 6 lb, and 120 watts.

In the far term, we can expect staring focal plane array FLIRs with dramatically better performance and smaller size than the CITV. Ford Aerospace, Hughes, Texas Instruments (TI), Martin Marietta, and Northrop are all developing FPA FLIRs.[28] Ford Aerospace, for example, produces IR FPAs for imaging-IR missile seekers, radiometers, and FLIRs. The company is now fabricating FPAs with more than 1000 elements (compared to the 180 in the common module M1 unit), and is developing units in the 3–5 micron range. Hughes and EG&G Reticon Corporation have also developed 512 × 512 platinum silicide 3–5 micron FPA detectors. RADC and Lincoln Laboratory researchers are working on 10–12 micron iridium silicide staring arrays.[29] Bell Laboratories has also announced development of gallium arsenide elements, which could have retinal-type image processing on the same substrate, with array sizes as large as 100 × 100.[30]

Probably the safest options for the far term are the SAIRS (Standardized Advanced Infrared Sensor) units being developed by TI and Martin-Marietta under contract to the Army Center for Night Vision and Electro-Optics. These are two very similar FPA 8–10.5 micron second-generation sensors. They are optimized both for operator viewing and for automatic target recognition input. The immediate application for SAIRS is the LHX (Light

[28]David Kales and Albert Tebo, "Markets and Technologies for Detectors Expand in 1987," *Laser Focus/Electro-Optics*, December 1987, pp. 89–98.

[29]David Hughes, "Platinum Silicide Detectors Incorporated in New Generation of Missile Seekers," *Aviation Week and Space Technology*, March 29, 1989, pp. 51–62.

[30]David Hughes, "Bell Labs Report Breakthrough in Gallium Arsenide Detectors," *Aviation Week and Space Technology*, September 5, 1988, p. 205.

Helicopter Experimental) platform, although M1 upgrades are also envisioned. The main differences with first-generation FLIRs are very accurate stabilization, use of 4000 detectors, addition of time delay and integration (TDI) to reduce noise, and incorporation of special techniques for scene averaging. These improvements are conservatively estimated to result in a 40 percent range improvement over the target acquistition and display system (TADS) unit,[31] with resolution to 0.04 mrad in narrow field of view. The TADS FLIR, used in the Apache, is itself much more sensitive than the M1 CITV FLIR. Prototypes of the SAIRS FLIR are expected in 1990.

Millimeter Wave Radar. Various submunition and vehicle programs have planned MMW radar systems—WASP, SADARM, COSTARS, STARTLE, ISTARTLE, and mini-STARTLE. Most are under development and some are "black" programs. A possible candidate for our application, because of its size and price, might be the Hughes WASP MMW radar. The unit is supposed to be less than 60 lb, with 200 watts power and a 7-in. diameter antenna, and be under $20,000.

The alternative STARTLE system has a 5 × 2.5 deg field of view and 2-sec frame time, but a 14-in. antenna. Efforts are under way to reduce the size of the system, although antenna size reduction should lead to somewhat lower resolution. Even use of a phased array antenna does not reduce the needed dimensions, although the antenna could be conformally shaped to the sensor pod or turret glacis. The mini-STARTLE system, now in its conceptual stage, is expected to have a detection range of 1.5 to 2 km, angular resolution of 1.25 mrad under good conditions, and search times of 1–2 sec for a 7 × 15 deg region. Targets must be moving at least 2 km/hr to be detected.

The major problem with MMW radar is its lack of resolution. It can penetrate all types of smoke, and detect moving targets out to 2–3 km (even farther with the larger STARTLE antenna), but it can not tell the precise direction of the targets. Against strong ground clutter, the system can be accurate only to about a beam width, which is about 1 deg for a 7-in. antenna. This is 18 mrad, more than a hundred times coarser than our needed resolution. With this accuracy, the system can fire at targets less than 100 meters away. A 14-in. antenna increases firing range to 200 meters. Greater power does not help resolution, and increasing the frequency from 94 GHz to 160 GHz takes the system into atmospheric and smoke absorption regions. Even bistatic techniques, in which a powerful radiator away from the vehicle sends the signal and the onboard antenna receives it, help only marginally, since the same resolution/antenna problems at the receiving site are present.

The second problem with MMW radar is that it is an active system, radiating energy and alerting the enemy. Tailoring the beam width, power level, and duty cycle may reduce the probability of intercept.

It appears that a limited role is likely for MMW. If bispectral smoke is blinding both FLIRs and video sensors, the MMW may then cue the operator to targets that can later be recognized and targeted by the other sensors when holes in the obscurance occur. The resolution is too coarse for recognition, and localization is insufficient for targeting, but MMW radar is the only choice in such obscuration. It also gives some complementary information to an automatic target recognition (ATR) system, such as range and doppler. A solid-state version has been demonstrated that can detect both tangential and radial motion of metal

---

[31]Cheryl Howard and Dennis Van Derlaske, *Standardized Advanced Infrared Sensor: A Program Status*, presented at 1988 Helicopter Society Meeting.

targets.[32] We see MMW radar as a strong possibility for the far-term sensor suite, particularly with new interest being generated for helicopter applications. A German version, the AEG Swallow, operates at 45 GHz and provides object detection out to 5 km. The system is large (13-in. diameter and 50-in. high, mounted over the helicopter rotor), but it has a reduced probability of detection through use of 30:1 pulse compression; a short 70 nanosec pulse is produced.[33]

Laser Radar. Laser radars are at an earlier point of development than MMW radars. The main participants are ERIM, Lincoln Laboratories, Ford Aerospace (the MICOS system), Rockwell (CMAG cruise missile laser radar), and Raytheon (COSTARS). The Lincoln Labs CO_2 unit is typical. It produces 12 watts of power and consumes 650 watts; it has a 0.2 × 30 deg view, it weighs about 15 kg, and it occupies 0.04 cu meter. It is supposed to be able to identify a target at 3000 meters with 90 percent probability. Presumably, it can also be used for laser ranging out to 5–6 km, although "moderately severe" weather conditions require at least 100 watts for this range. The main problems are that the system takes many seconds to scan an area, and that laser scanning is an active process, alerting the enemy to one's presence. The advantages are that it provides data (three-dimensional shape, vibration signature, detailed outline) that other sensors cannot produce. A laser radar may be used for target identification after cueing of a specific threat by the other sensors. Laser radars also have potential for remote sensing of airborne chemicals and for taking out enemy sensors through localized heating or blinding. Finally, they may be used for retroreflection sensing, where the beam is reflected strongly from an enemy vehicle's optic or FLIR lenses, showing up as a flash.

The laser radar will probably be available only for the longer-term (10–20 year) system. It requires a similar level of cooling as the FLIR, and since both operate at around the same wavelength, the same optics could be used for both. The thermal detector array could be used for sensing the laser returns. A combination FLIR/laser radar unit is being developed by Eltro.

For the near term, the new CO_2 laser ranging system present in the TI tank thermal sight (TTS) should be sufficient for target ranging. The unit is quite small and light compared to the other sensors.

Hard Optics. The mast pods provide primary sensing capabilities for the future vehicles, but ancillary sensors are needed for wraparound vision and general orientation, some driving, and redundancy with the other systems. The main choices are (1) wraparound hatch visors, (2) a set of vision ports, and (3) rotating panoramic periscopes.

The wraparound visor would be a unity power transparent armor shield that forms the lower forward portion of each elevated hatch. This visor, described in Sec. IV, provides about 220 deg of vision. The advantages are that it has few occluding seams and minimal registration problems, provides good orientation cues to the crew, maintains the NBC protection, and does not intrude on the crewspace. Such a visor would also allow the user to view the cathode ray tube (CRT) displays in open hatch conditions, because it would have variable tinting to reduce sun glare and block lasers. The operators should be able to use night vision goggles or conventional binoculars with the visor in place.

[32]Philip Johnson, "Tank Vision Systems of the Future," *Military Technology*, No. 6, 1984, pp. 55–56.

[33]Philip J. Klass, "European Firms Increase Efforts To Develop Millimeter Wave Radars," *Aviation Week and Space Technology*, September 5, 1988, pp. 153–155.

A set of unity vision ports seems less advantageous. Here the user flips down a set of 50-deg wide-angle periscopes (four around each hatch). They maintain orientation, as does the visor, but the ports have registration problems and blind areas.[34] They also intrude somewhat on the crewspace, restrict ingress and egress through the hatch, and are difficult to use with binoculars or goggles.[35] They do provide more protection against weapons than the visor does, because the visual path is angled.

There are a wide variety of direct optics periscopes available. Fairly conventional choices would be (1) a pair of Baird model 350 biocular night vision sights, providing each operator with a 44-deg field of view rotatable over a 135-deg field; these have auto brightness control and flash protection and require two 4-in. diameter holes through the armor over the operators; (2) eight Sopelem CN2-500 passive night vision periscopes, each with a 50-deg biocular field but no rotation; each would result in a 4 × 8 in. hole through the armor; and (3) two Sagem M389 panoramic sights, rotatable dual magnification (2× and 8×) units suitable for emergency weapon firing; each armor hole is roughly 7 in. in diameter and each unit weighs 31 kg.

A rotatable periscopic sight such as the Sagen unit is a special-purpose device; the user electronically scans an area, viewing the scene by any of several devices—eyepiece, screen, or helmet-mounted display. There are orientation problems with the eyepiece or screen displays, but the user has substantial flexibility. He can call for different magnifications and perform fire control functions directly. The signals can be sent by a coherent fiber optic bundle, so that the main vehicle network is not relied on. If the rotatable sight is combined with a helmet-mounted display (HMD), the orientation problems would be minimized, just as with mast sensors and HMDs.

A combination of visor hatches and a single gunner's periscope seems to be the most effective set of hard optics for future vehicles. Integration of a gunner's periscope with a helmet-mounted display is recommended for the far-term auxiliary vision system.

Radar and Laser Warning System. Threat warning is alerted by sensors mounted on several points on the chassis and turret. The system is tuned to laser and radar frequencies. The best current choices seem to be the Racal Savior radar and laser warning receiver, the Perkin-Elmer AN/AVR-2, and the General Instrument AN/ALR-80.[36] These systems identify the type of threat, along with rough direction (generally eight sectors). The Racal unit is approximately 1/4 cu ft and can store six threat signatures. The somewhat larger General Instrument unit can store some 1000 threat signatures.

Acoustic Sensors. Much of the important acoustic sensor work was done by RCA under the REMBASS (Remotely Monitored Battlefield Sensor System) program.[37] This system uses acoustic, infrared, seismic, magnetic, and other sensors to detect and classify men and vehicles. It is in service with the U.S. Army for forward area intelligence. The sensors themselves are remotely emplaced (by hand, artillery shell, or aircraft) and communicate using an integral FM radio. A central monitoring station collects and processes the data.

---

[34]W. K. Earl, *Human Factors Engineering Design Criteria for Future Systems,* Army Research Institute Report ARI-RP-84-05. March 1984.

[35]W. K. Earl, *Human Factors Evaluation of the M1 Combat Tank in Operational Test III,* Army Research Institute Report ARI-RR-388, December 1984.

[36]Stefan Geysenheyner, "Radar and Laser Warning Receivers," *Military Technology,* February 1986, pp. 36–43.

[37]*Jane's Avionics,* section on Electro-Optics, Jane's Publishing, New York, 1987–1988.

In our applications, a basic set of four microphones may be mounted on the telescopic masts, under a raisable cover. The set should give directional information and threat typing of targets out to a maximum of 1 km.

Electronic Countermeasures. All of the external optics on the vehicle will have to have protective coatings that quickly react to high-power pulsed lasers. Wavelength-selective reflective coatings may also be used, but may overlap the frequency of the FLIR and laser sensors.

Once a threat is detected, various countermeasures are possible, including jamming of optical and radio frequencies, decoys for lasers and thermal sensors, and smoke for obscuration. For light armored vehicles, threat response may also include automated reactions to ATGMs, such as grenades and Gatling guns.

To a certain extent, the vehicle itself may be low signature. It may have skirts that drop over the roadwheels, suppressing noise, dust, and thermal signature. The chassis may be covered by radar absorbing materials, and the engine inlets may be thermally controlled.

Sensor System Configuration

This subsection describes some design choices made to interface and configure the electronics systems. The primary issues explored are how to mount the sensors, how to stabilize them, and how to route signals from the external sensors to the onboard signal conditioners and displays. Recommendations for each aspect are given and then incorporated in our designs in Secs. IV and V.

Sensor Mountings. Most designs for future ground antiarmor vehicles assume the crew operates primarily in the hatch-closed mode. Open-hatch operations expose the crew to shrapnel, direct fire, beam weapons, and NBC conditions. Accordingly, we need to mount the sensors at the highest point on the vehicle for extended, full-capability search and engagement activities. The sensors should have 360-deg viewing, with sensor pods well above the protected crew. They should have multi-axis stabilization and small presented cross section. At the same time, they need thick armoring. Our choices are (a) to hard mount the pods on the forward edge of the turret roof, (b) to mount the pods on vertical telescopic posts, and (c) to mount the pods on rotating arms attached to the sides of the turret. These options are shown in Fig. 20. The first choice—mounting the sensor pods on the turret roof—is the simplest, most stable, and least expensive option. It also results in the lowest contribution to turret cross-sectional area. The approach is used widely for new designs, but it limits sensor height and assumes that platform or mirror movement is sufficient for sensor elevation and depression. Side views from the sensors are also frequently obstructed by other turret projections (hatches, wind sensors, machine guns, etc.).

The second option, mounting on telescopic masts, allows raising the pods several meters above the turret. The variable height provided by the masts lets the user search for foliage holes and peer through them. The pods can also be retracted down behind armored shields. Mast travel may aid in the stabilization process during movement, particularly during large suspension travel. Finally, if mast excursions on the order of several meters are possible, a MMW radar may be used for accurate targeting through integration of pulses over the movement range. This, of course, requires significant amounts of processing, and should be considered only a far-term possibility.
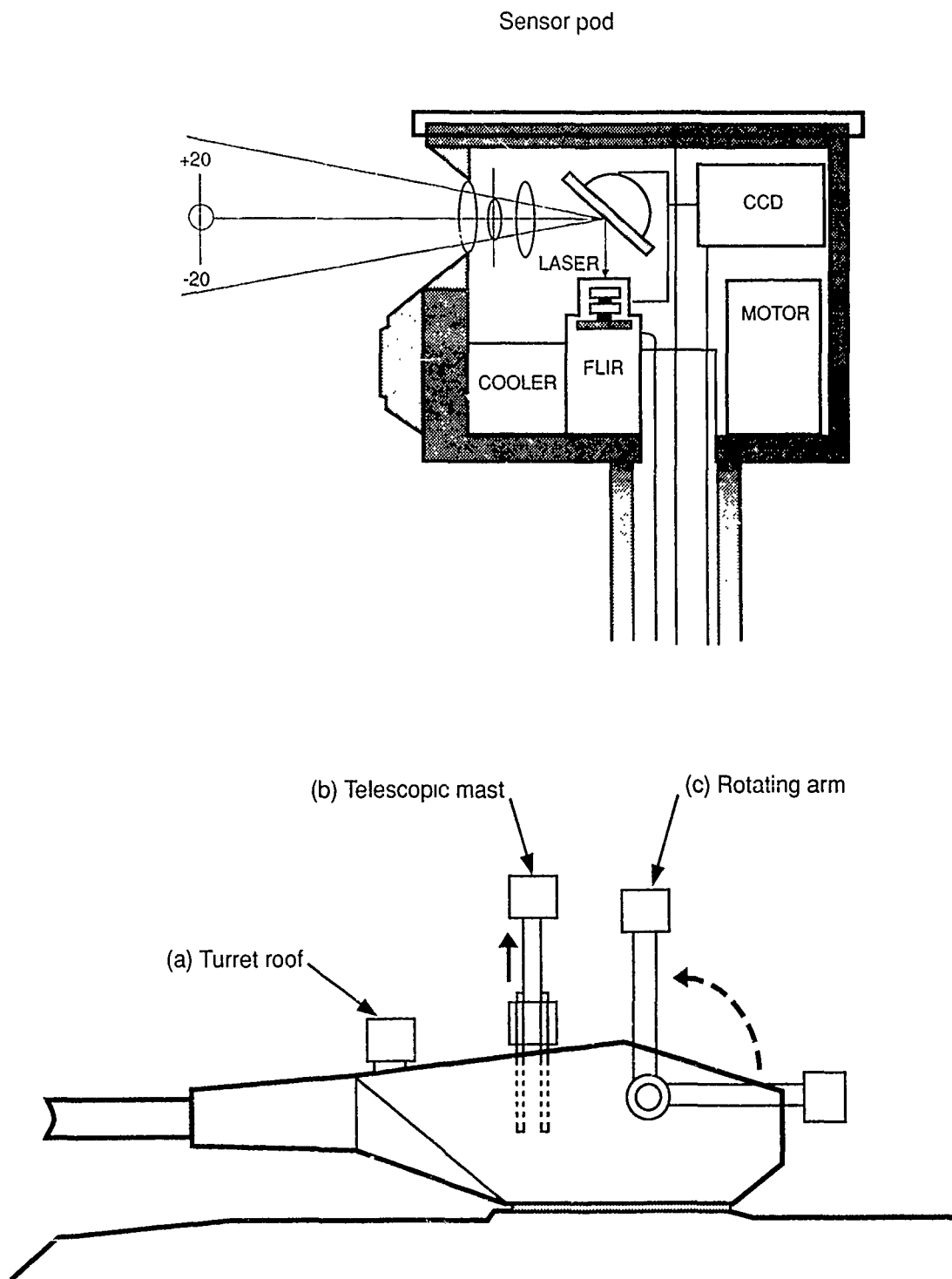
Sensor pod

Fig. 20—Sensor pod and sensor mounting options

Mounting the pods on rotating arms is an intermediate complexity approach. The sensor pods swing up from a rear, protected, horizontal position to an upright viewing position several meters up. The solid arms should be more rigid than telescopic masts, and the arm rotation may help in the stabilization and elevation/depression actions. The design does not offer the flexibility of telescopic masts, however. Partial height positions may not allow sufficient forward view, and the stowed position severely limits sensing.

For our purposes, the vertical telescopic mast approach appears to be the most satisfactory. Used in our designs in Sec. III, this design provides the greatest flexibility and performance. The speed and extent of mast travel will have to be determined from analysis and simulation runs.

Sensor Stabilization. The image must be stabilized vertically and horizontally, especially when the tank is moving. Stabilization is best done in "director" mode, in which the gun and sensor are not lashed together. In this situation, the sensors can access multiple targets and achieve greatest frequency response. The major considerations of stabilization are frequency response, accuracy, and unit size. Frequencies up to 10 Hz must be compensated, and the level of stabilization needs to be better than 0.1 mils. This typically enables a 2-meter target to be recognized at 4000 meters at 10× magnification.[38]

Our stabilization options are: (a) to mount the entire armored sensor pod on a vertically and horizontally rotating baseplate driven by stepper motors, (b) to mount the sensor package and stabilization motors inside the armored pod and use the "swept area" inside for sensor movement, or (c) to use a stabilized mirror assembly to focus the image on hard-mounted sensors inside the armored pod. Figure 21 shows examples of the three options.

The first choice, stabilizing the whole pod, is used in some sensor applications for robotic vehicles and aircraft. Pod cross section is small because the armor can be wrapped tightly around the sensors. In the MBT missions, however, the sensors would be frequently subjected to small arms fire and fragments, so that at least 50 mm of armor is needed. With this level of protection, each stabilization motor would have to contend with a minimum of 200 kg, resulting in poor frequency response or large motors (the motor normally does not have to move the sensor, just keep it stable with the horizon while the platform pitches and rolls beneath it; nevertheless, large torques may be present).

The second approach stabilizes the sensor package inside the armor, but requires several inches of swept area around each component for travel. This reduces the stabilizing motor size compared to option one, but greatly increases the sensor pod size and weight. It also subjects the sensitive scanner components to compensating forces (up to 10 Hz or so).

The last approach, using stabilized mirror assemblies, is a commonly used configuration for hard optics. Since only the mirror is moved, the swept area inside the armor is minimal, frequency response is excellent, and actuator size is small. We have several boresighted components in our system (TV, FLIR, laser rangefinder), so several mirrors may be necessary. The mirrors may be all combined in one unit, with different surfaces for each sensor, but this would result in a large mirror with a significant swept area. A more appropriate design would be to use a dichroic mirror, reflective to FLIR wavelengths but transparent to optical energy. This minimizes the mirror size and the vulnerable (and expensive) window. As shown earlier in Fig. 20, the TV sensor must move with the stabilized mirror. The movement

---

[38]Mark Hewish, Gerard Turbe, and Paul Turk, "Tank Fire-Control Systems," *International Defense Review*, No. 6, 1988, pp. 765–777.

2 inch armor

(a) Stabilized pod

Azimuth,
elevation
motors

(b) Stabilized sensor package

Stabilization
clearance

(c) Stabilized mirror assembly
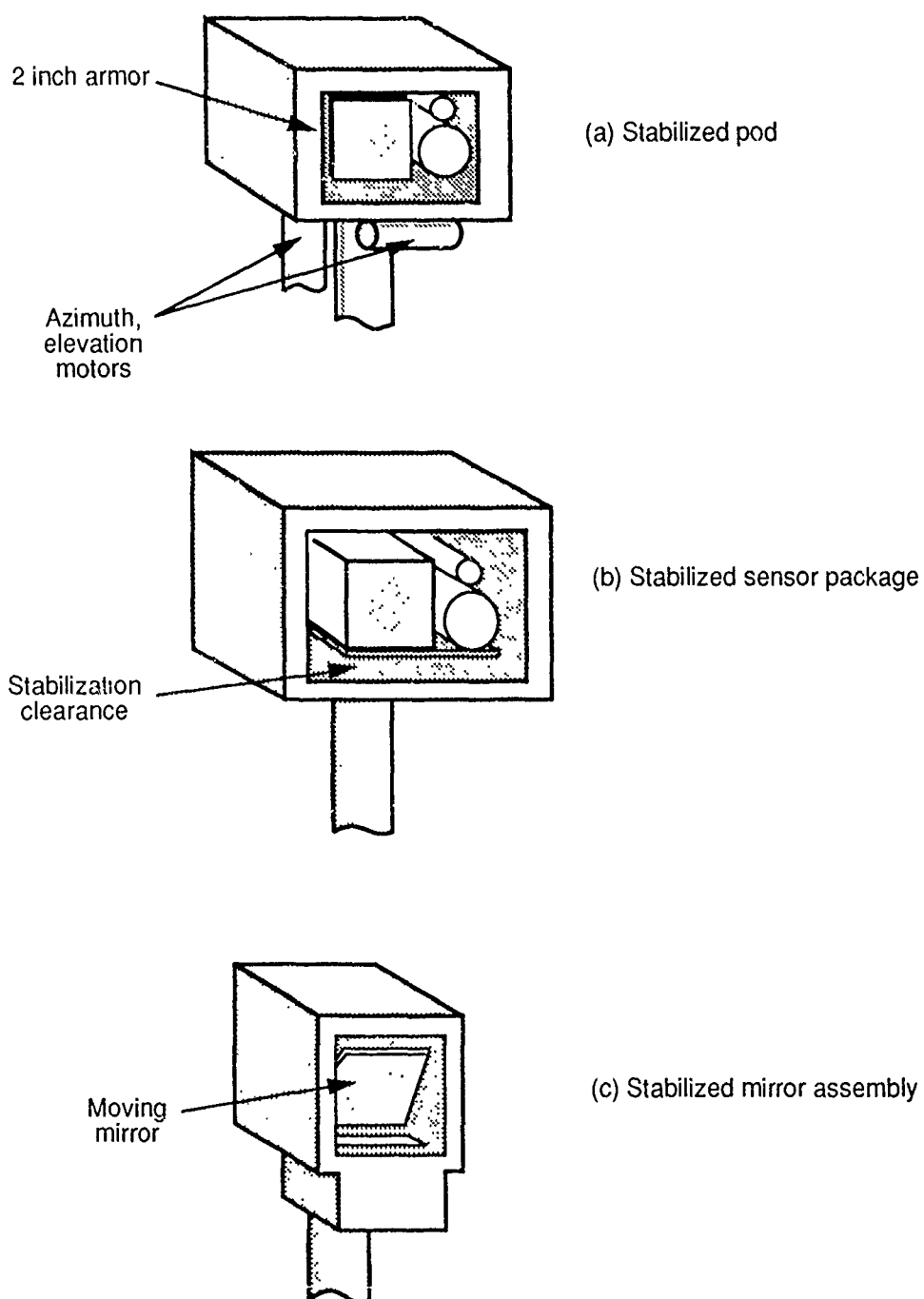
Moving
mirror

Fig. 21—Sensor stabilization options

of the TV sensor should not result in appreciable mass or vibration problems. The much larger FLIR sensors would be stationary.

This dichroic stabilized mirror approach appears to be the best option for our designs. In all of these stabilization techniques, 17 to 19 bit optical encoders should be sufficient to maintain accuracy to 0.1 mrad. Some of the few stabilization systems currently capable of maintaining this accuracy are the sight heads on the French SFIM 580 sight, and the Ferranti type 234 thermal imaging/laser system.[39]

Signal Routing. Video signals must be sent from sensors to displays over a link. Fiber optic lines give the greatest bandwidth, fewest emissions, and cleanest signals. Because the sensor masts and turret both rotate, however, the fiber optic cables must either twist in passages or transmit through special optical slip rings. Litton produces optical slip rings, and two-color versions with LED transmitters for two separate signals have been demonstrated. Unfortunately, they are expensive, bulky (7 in. diameter), and have losses. The fiber optic cables should be able to twist sufficiently in the mast housing and turret passages. We do not expect multiple 360-deg rotations by either the turret or the masts.

A second question is whether the sensor scanning elements themselves can be remote from the optics, resulting in minimum size pods. Recent advances in fiber optic materials show promise for transmitting 10 micron FLIR signals.[40] Separate coherent bundles would be used for the optical and IR sensors, with removal of the detector arrays, scanning electronics, and cooling systems to protected positions down in the hull. With 1 mil fibers, a 1-in bundle would transmit a 1000-line image. The laser ranger would have to remain in the pod, but the overall cross section of the pod would be much reduced. The same mirror assembly used in the normal (nonremote) configuration could be used. Coherent fiber optic links appear to be a strong option for the far-term system. Some resolution would be lost compared to a close-coupled lens and scanner system pod, but the system would be smaller and less vulnerable.

Hatch Configurations. Crew hatches, one of the most difficult design tasks for reduced crew armored vehicles, assume a special importance because they have to compensate for the loss of all-around commander vision. At the same time, they must not introduce substantial vulnerability near the normal aim point. The key issues are:

- The hatches should allow the crew to raise their heads so that eye level is above the frontal glacis. They can then look out through an armored visor (a curved or sectioned polycarbonate window several inches thick). Each crew member's visual envelope should be at least 180 deg wide × 30 deg high.

- The hatches should allow normal crew ingress and egress without having to rotate the gun from the forward position. This requires a clear opening of at least 12 × 20 in.

- The forward turret ring and gun mechanism should be protected against KE threats (1300 mm line of sight armor thickness), with the protection extending from

[39]*Jane's Avionics,* section on Electro-Optics, Jane's Publishing, New York, 1987–1988.

[40]Herbert Kaplan, "Photonics at Work: Long-Wavelength IR Fiber Optics," *Photonics Spectra,* April 1988, pp. 82–84.

the hull glacis to the gun overhang. If KE protection levels cannot be attained, CE protection (600 mm) should be incorporated. At the same time, there should be substantial top attack protection for the crew.

- The hatch opening mechanism should be manually operable in event of damage or power outage.

- Changing from visor to full armor should not compromise the NBC seal.

The hatch design should also follow good engineering practice. The hatches should not be overly complex or have multiple axes of movement. They should not have large unsupported masses, and they should not compromise the structural integrity of the vehicle. There are four options that are possible candidates.

1. The *full ring* design, while somewhat massive, is the only design that satisfies all the above criteria. It consists of a large diameter ring that fits between the hull and the gun, rotating on the same axis as the gun and autoloader (see Fig. 22). When the crew is entering or exiting the tank, one of the sets of open hatches is rotated to the forward position. There is then minimal obstruction to ingress and egress. When the crew is driving, searching, or targeting, but is not under direct attack, it can rotate the visor enclosure to the front. The enclosure is a sealed box into which the crew can raise their heads and look out through a panoramic visor. There is sufficient room for use of binoculars or night vision devices, and there is no obstruction between the crew members, so that they can point and coordinate. The box gives protection against small arms and fragments, and maintains a sealed NBC environment. When the crew is under direct attack, the members can drop down into a reclined position in the crew module and rotate the massive armor section to the front. The armor section fits snugly between the gun and the hull, and in combination with a fixed armor block in front of the turret ring provides full frontal KE protection, removing the shot trap. The armor also gives top attack protection for the crew. When either the visor block or the armor block is forward, the ring does not add cross section area to the front. In fact, when the armor block is positioned behind the gun, it protects the engine compartment. Ammunition can be loaded into the hold in any ring position, since this is done through stationary hatches at the rear sides of the gun. The stationary hatches also act as blow-off panels and have doors giving them top attack protection.

Special advantages of this design are that the crew can turn the visor enclosure or the armor block in the direction of the threat, increasing vision and protection. Also, when the exit hatches are open, the visor and armor are far enough away to allow almost 300 deg of vision (combined between the two crew members). A minor benefit is that the armor block, when moved to the rear shifts the vehicle center of gravity slightly to the rear.

The main problem with the full ring seems to be maintaining NBC seal when rotating from visor enclosure to armor block. Covers will have to be slid over the crew compartment holes before rotating the ring, or the full ring will have to be sealed. Also, the 12-ft diameter ring will probably take more time to rotate than it would take to open a normal hatch. For size comparison, the current M1-A1 turret ring has a roughly 9-ft outside diameter, extending over the track wells, and has environmental sealing.

Armor
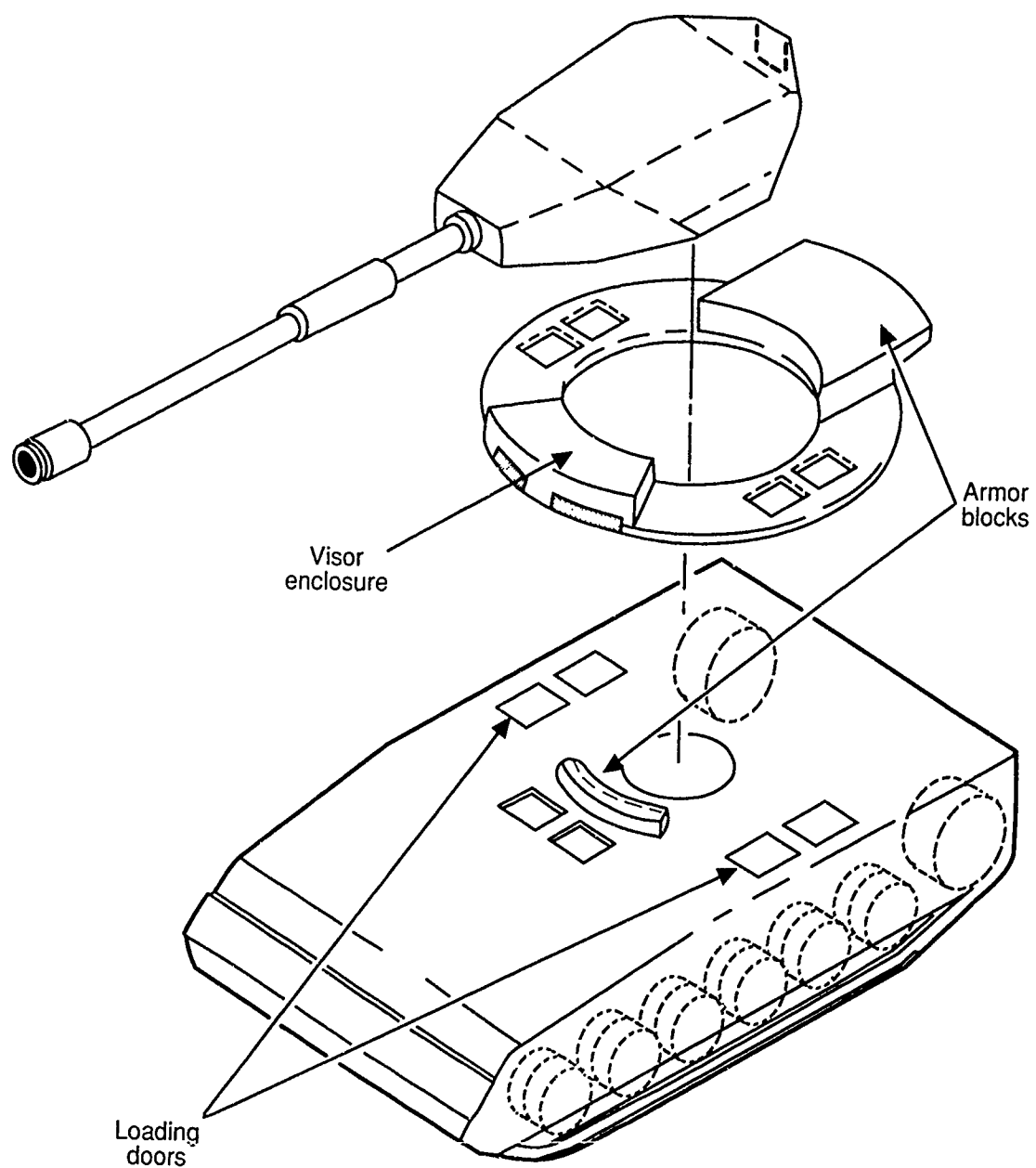blocks

Visor
enclosure

Loading
doors

Fig. 22—Full ring hatch design

2. The *partial ring* is a variant of the above approach, using only a third or so of the full circle (see Fig. 23). The crew has full open hatches when entering or exiting the tank, or when operating in a nonhostile environment. On each side of the open hatches are nested visor modules and armor blocks. The visor modules are on the outside and move in on tracks to cover the crew. The visor modules meet in the center, forming a single enclosure for the crew, with the armor blocks forming the outside walls of the box. The crew should have as much room as in the full ring design, but somewhat less side vision. When full protection is needed, the crew drops down into the crew compartment and the armor blocks are slid into the visor enclosures. Armored lids drop down over the visors themselves.

The problems with this design are (1) reduced side vision compared to the full ring (in both open hatch and visor modes), (2) slightly reduced armor protection, because of the visor thickness taking part of the armor depth, (3) larger front cross section when visor or armor is to the side, (4) slightly more difficult ingress/egress compared to the full ring. and (5) problematic NBC sealing, with all the sliding and enveloping surfaces.

3. The *rotating counterweight* is a self-contained hatch, with no components moving over the hull surface. As shown in Fig. 24, the hatch is circular, with two parts (lid and armor block) hinged together. When the visor section is rotated forward, the crew member can look out through the window. He can rotate the visor in the direction of targets and can close it quickly by pulling it down into the hatch opening. To enter or exit the tank, the crew member rotates the hatch out 90 deg and lifts the lid with visor attached. The lifting is easy since the rear armor block counterweights the hatch. For maximum armor protection, the crew member rotates the hatch 180 deg, putting the armor block to the front. The armor, in combination with the fixed armor to the rear of the hatches, should provide the gun CE but not KE protection. Once down in the hull, the crew member pulls a spall liner over his head.

The drawbacks with this design are (a) only CE protection for the turret ring rather than full KE protection, (b) more difficult ingress/egress compared to the full ring design, and (c) limited top attack protection for the crew.

4. *Lift and swing-away* is a lightly armored hatch, designed for quick operation. As shown in Fig. 25, the hatch has an armored ring that protects the visor. When the armored ring is raised, the crew member has full vision out the front and partial vision to the side. The visor and armor swing-away to the side for entry and exit. The crew can then partially avoid the gun overhang when getting in and out. NBC sealing is simple, just as it is with the counterweight design.

The problems with the simple hatch are (a) very limited frontal armor protection for gun and crew, (b) very limited top attack protection, (c) more difficult ingress/egress than with the full ring, and (d) somewhat limited side vision.

In sum, we have a wide range of hatch and armor designs that vary in complexity, protection, and performance. The more complex ring designs are heavy and will probably require addition of a floor hatch for emergency exit. The simpler self-contained hatches result in protection and performance compromises. For now, we are specifying the simple "lift and swing-away" version in our designs in Secs. IV and V.
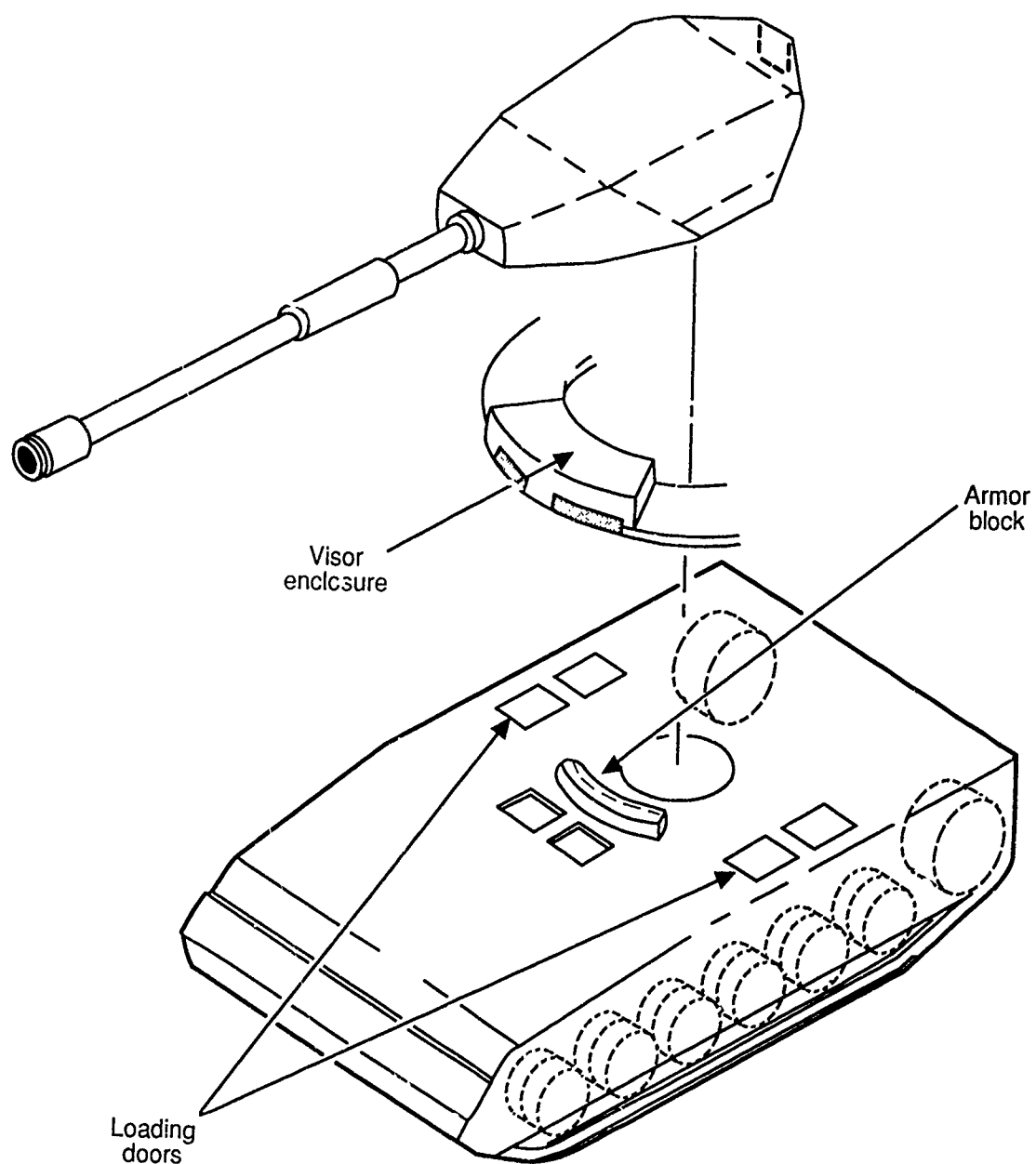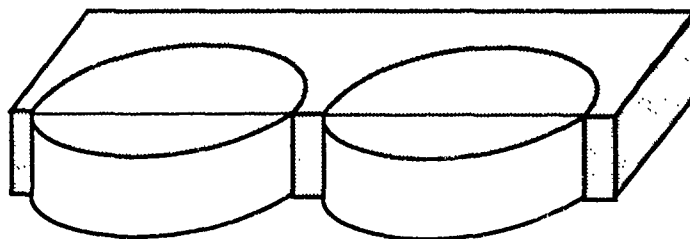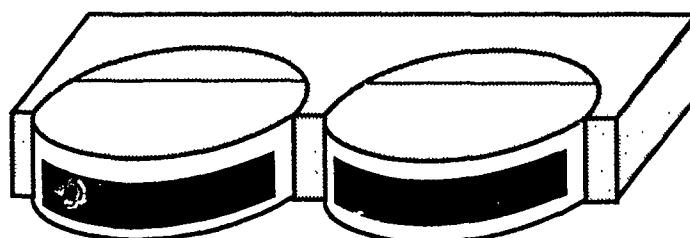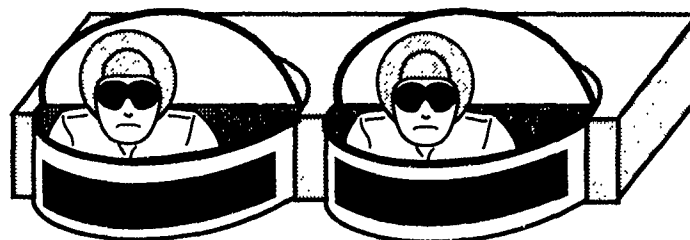
Fig. 23—Partial ring hatch design

(a) Hatch closed, armor forward

(b) Armor rotated back, visor forward

(c) Hatch open, ingress/egress possible

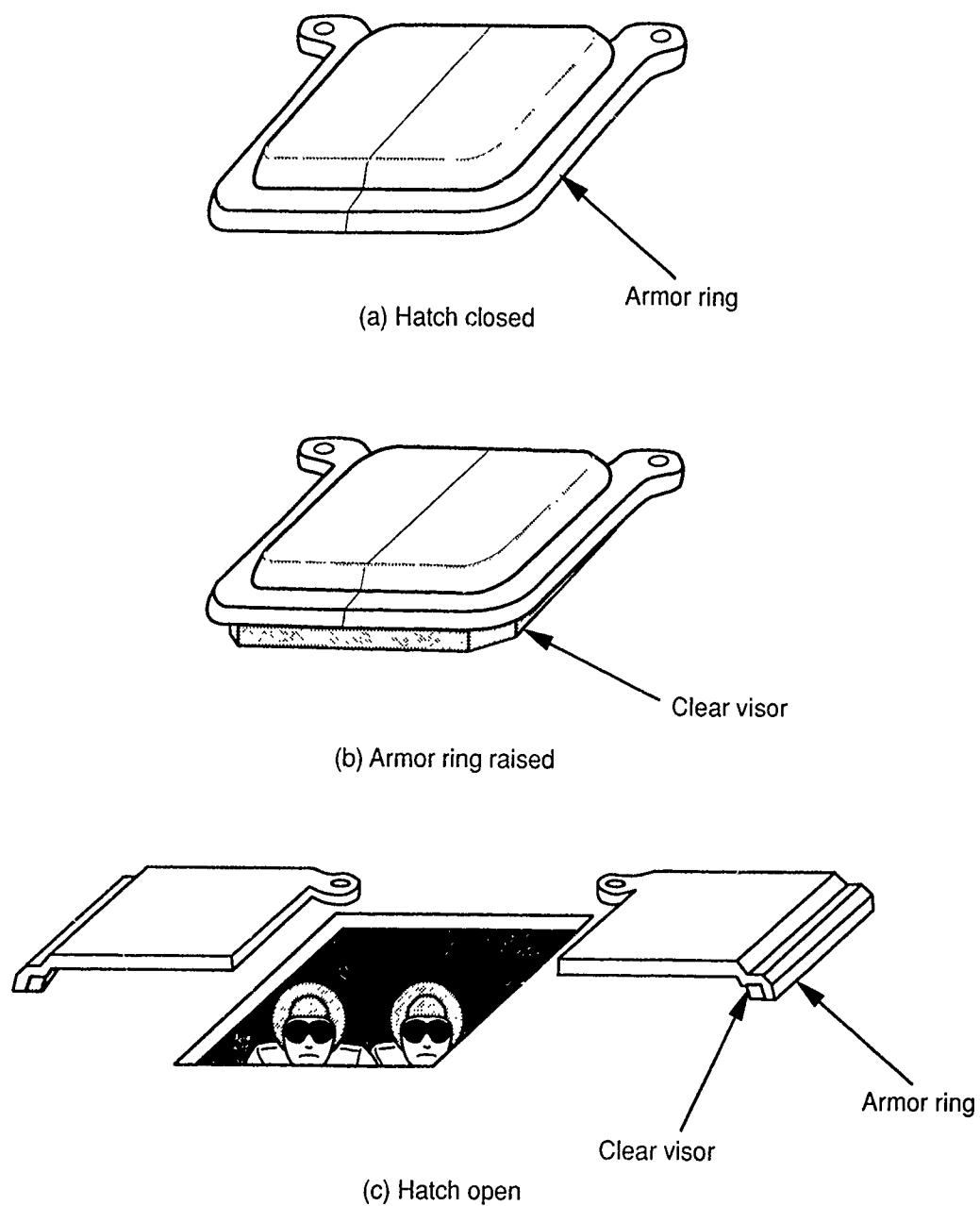Fig. 24—Rotating counterweight hatch design

(a) Hatch closed

Armor ring

(b) Armor ring raised

Clear visor

(c) Hatch open

Clear visor

Armor ring

Fig. 25—Lift and swing-away hatch design

COMMUNICATION AND POSITION LOCATION SYSTEM

Current generation armored vehicles typically make do with simple high-frequency (HF) radios for voice communication, but HF will not be sufficient for transmitting the expected amounts of data about sensing contacts, plans, commands, and data requests. Also, voice channels normally do not provide adequate security and do not support position location. Combat vehicles need secure high-bandwidth digital links accurate position location, and automatic situation updating.

We see two stages of communication system development. The first, near-term system is based on SINCGARS (Single Channel Ground/Airborne Radio System). As made by ITT and other manufacturers, this 19 kbit/sec unit uses FM line-of-sight transmission with digital and verbal capabilities. The system weighs 13 lb in vehicular form and can be augmented with a Lear Siegler VNETS navigation system. The navigation system is accurate to 1/2 deg orientation and 2 percent of distance travelled. A similar ring gyro navigation system (MAPS) by Honeywell has shown accuracy to 0.1 deg and 0.1 percent of distance travelled, but it is larger and considerably more expensive.

An additional communication system required for the near term is an active noise reduction unit. This system electronically cancels the high interior noise generated in an armored vehicle and passes on communications within the headset. Plessey Military Communications makes such a unit.

For the far term, we should be able to incorporate a class 2 joint tactical information distribution system (JTIDS)/position location recording system (PLRS) multichannel system. Now in development, the Singer/Rockwell AN/URC 107 class 2 terminal consists of a communication-navigation-identification processor and a separate receiver module. The unit has a 238 kbit/sec transmission rate, two voice channels, two 30-in. antennas, and 300-km range. It produces 200 watts output from 1400 watts input. Unfortunately, even this transmission rate is too slow for video or map data. A data compression device will have to be added.

JTIDS/PLRS has an integrated position reporting system that is accurate to 15 meters. The unit also maintains estimates of all friendly vehicles, aiding in IFF. The system uses time-based triangulation to tell position, requiring minimum intervisibility and net size conditions to be met. Eventually, the system will be integrated with onboard fire-control systems. There is some question about continued development of the program, but an enhanced PLRS system, known as E-PLRS or PJH, should be available regardless of the development decision.

DISPLAYS AND CONTROLS

As in most modern armor systems, there is little room in our chassis designs for controls and displays because of the extreme requirements for armoring the crewspace against KE weapons. These space constraints obviate the possibility of providing true panoramic CRT or projection displays. Instead we see each operator having several medium-size color displays in the near term, along with a wraparound transparent armor visor in the hatch. For the far term, we should be able to augment the system with helmet displays, which provide more panoramic and natural views.

In our near-term two-man crew designs, each operator will have his own set of two-color CRTs and will share a large monochrome flat panel status display. Color displays are essential for discriminating targets against clutter, and color is helpful for depicting elevation and cover on map displays. A central status display is shared in our design because a replication for both operators would make the display control panel too wide for the crewspace. Also, this display will be accessed less frequently than the map and sensor displays, usually by only one crew member at a time. When both crew members refer to the status display, they will typically be coordinating. The map, sensor, and status displays will be touch sensitive and surrounded by programmable touchpads. Each operator will also have two side sticks (for most continuous control functions). Finally, the operators will have voice synthesis and recognition systems. All of these systems, along with extensions for three-man crews, are described in more detail below.

Two problems with the displays are brightness and orientation. When in hatch-open mode, for instance, the color displays and side sticks will swing up with the operators, perhaps resulting in problems with display brightness compared with outside light levels, even with automatic brightness control. Orientation is even more problematic. With fixed screen displays, the operators will have a difficult time perceiving the relative orientations of chassis, sensor, gun, and terrain. This should be mitigated somewhat in the far-term system, because the image of the planned helmet-mounted displays will pan as the operator turns his head.

CRT Displays

The terrain map and situation display should be a medium-size (5–7 in. square) color CRT. A CRT is necessary in the near term, in spite of its disadvantages in bulk, reliability, and power requirements compared with flat panel technology, because it is the only near-term system with sufficient color saturation, grey scale, and resolution. A recommended choice is the Honeywell multipurpose color display, a 5 × 5 in. shadow mask CRT with stroke, raster, or combined graphics in 16 colors. When used in the F-15E, this unit displays video images, JTIDS messages, and system status graphics. The display is surrounded by 20 programmable touchpads. Dimensions are 7 × 7 × 15 in. and weight is 26 lb. Television resolution is 350 line pairs from 10 MHz video bandwidth. The screen should be sufficient for the horizontal map display, although the larger 6 × 6 in. screen described below for the direct sensor scan display would be easier to work with.

The perspective display (showing direct sensor outputs and overlays) could be implemented on Honeywell's "smart" multifunction color 6 × 6 in. display. This developmental display has similar characteristics to the 5 × 5 in. system, but also has rapid switching between formats, controlled by 1553B bus commands. The system has dimensions of 8 × 8 × 15 in. and weighs 36 lb. This is the minimum size needed for the perspective display. A near-term alternative is the Loral Sigma display beam index system, which does away with the shadow mask to provide greater brightness.

As another alternative to the above units, Loral has in limited production a color AN/ASA-82 large screen CRT display with a built-in TI-9900 microprocessor. Used in classified aircraft electronic warfare applications, the screen is 9 × 12.7 in., with 1024 × 1024 addressability and very fast raster writing (100,000 in./sec). Its dimensions are 18 × 14.5 × 22

in. and it weighs 73 lb. It would be a possible alternative to the above two displays, showing all the status, map, and sensor information in a single-screen, much like that planned for McDonnell-Douglas' prototype Big Screen and Singer's developmental 14-in. screen. Unfortunately, its dimensions are too large for the current crew station design. Also, the multiple screens of the recommended system provide redundancy and allow more natural positions for touchpads than does a single screen system. It is even possible (as is done in Lockheed's Electronic copilot system) to display the same scene across the two adjacent CRTs, resulting in a panoramic screen.

Sizing and positioning of the CRTs should take into account human factor considerations. The eye has a 2–3 in. foveal vision area, with a 180–200 deg peripheral vision area, and a typical 30 deg preferred viewing cone. At the normal 18 in. viewing distance, this translates to a 9–10 in. display face or set of faces. A refresh rate of at least 50 Hz is also needed, with maximum resolution of 2000 lines. This results in a data rate on the order of 500–700 MHz, although much lower rates (20–50 MHz) produce images that are quite acceptable.

Flat Panel Displays

The vehicle status, diagnostics, and communication display should be viewed on a large flat panel. A good choice is the 8 × 8 in. Computing Devices electroluminescent display (monochrome, 500 × 500 pixels) with a touch sensitive screen. The touch sensitive (1/4 in. resolution) IR grid used on this device can also be mounted to the above CRTs.

Full color is desirable for the status and diagnostic functions, especially for alerts. Two colors are the most currently available with high-resolution flat panel displays, and most experts agree that high-density presentations should be made with full color. In the far term, we may be able to use Collins' or GE's developmental full color liquid crystal flat panel displays.[41] These 3-in.-thick displays have excellent brightness but do not have the grey scale capability of CRT systems. Vacuum fluorescent displays (VFDs) are another candidate. These appear to have the most promise for full color flat panel display. In the next few years, we expect that all of the CRT displays may be replaced by full color, high-resolution flat panel displays.

Unlike the map and sensor displays, only one status display seems necessary for the two operators. The other displays give different views when the sensors are pointed in different directions, and so require separate displays. In some of our three-man designs, the third man may have a separate flat panel display for some or all functions, depending on the available room.

Helmet-Mounted Displays (Far Term)

A helmet-mounted display (HMD) takes far less room and provides a wider field of view than any of the multiple CRT and flat panel designs described above. It also gives responsive sensor control by head pointing and provides good cues for orientation and depth perception. However, the technology is still insufficiently mature (particularly in pointing accuracy and

---

[41]"Revolution in the Cockpit," *Aviation Week and Space Technology*, April 11, 1988, pp. 59–75.

high-magnification stabilization), so we plan to relegate this extremely promising technology to the far term.

The HMD concept is quite different from that of a head-up display (HUD). The HMD projects a scene on the user's visor or eyepiece that is aligned with his head direction. A HUD, on the other hand, projects the scene on a screen mounted directly in front of the operator. With either system the operator can concentrate on control actions in a head-up/hands-back mode with all major control elements for the mission phase on the throttle and control sticks. The advantages of the HUD in aircraft—compensating for brightness differences from outside to inside, reducing vertigo problems associated with eye movements and vehicle maneuvers—are not as prevalent in a buttoned down tank. Also, HUDs typically display monochrome symbology, not the high-resolution color displays provided by HMDs. Full color displays are essential for search, targeting, and navigation.

The Honeywell IHADSS (Integrated Helmet and Display Sighting System) has high-resolution 1000-line imagery from slaved IR and LLLTV sensors, along with overlaid vehicle information. Helmet orientation is sensed using rotating IR light beams. The projected image is 30 × 40 deg. The latest version is in production for the AH-64A helicopter, and has been successfully used in remote driving tests by General Dynamics (GD) land systems. A developmental version is being readied for armored vehicle use. Magnified imagery can be projected, but must be stabilized to avoid operator disorientation.

The Ferranti and Agile Eye helmet-mounted sights are lower-cost alternates to the IHADSS system. The Ferranti system includes a high-resolution four-grey-scale monochrome CRT projected on the pilot's visor, three-axis magnetic helmet orientation sensor, and a roll-stabilization system. The unit size is roughly 5 × 7 × 12 in. long, with a 0.4 lb optical sight. It has been tested in British helicopter trials. The Agile Eye system, developed by McDonnell-Douglas and Kaiser Electronics, has similar characteristics, along with abilities to designate and follow multiple targets outside the immediate visual field.[42] A similar McDonnell-Douglas Falcon Eye system and automatic target handoff system is being used in the F-16.

A next-generation helmet-mounted system is the HITADS (Helmet Integrated Tracking and Display System) by Bendix. This HMD uses holographic optical elements and fiber optic image transmission. It also features an angular pointing accuracy of 20 mrad root mean square (RMS) and a time response of 20 msec.[43] The pointing accuracy may be good enough to designate a target, although it is not accurate enough to perform fire control against a 3-meter target at 3 km, even with high magnification. Day and night fields of view measure 30 deg horizontally and 22 deg vertically.

A helmet-mounted simulator projection system being developed by the Air Force Human Resources Laboratory (AFHRL) and CAE Electronics may have potential for far-term development. The system uses fiber optic bundles to relay coarse background and detailed area-of-interest graphics to a pair of pancake window eyepieces in front of the pilot's eyes. The system monitors eye direction and places the high-resolution image in that position, electronically feathering the edges with the low-resolution background. During saccade

---

[42]Stanley Kandebo, "Navy to Evaluate Agile Eye Helmet-Mounted Display System," *Aviation Week and Space Technology*, August 15, 1988, pp. 94–99.

[43]Bill Sweetman, "Combat Cockpit of the Future," *International Defense Review*, No. 4, 1988, pp. 363–366.

(rapid eye movement) a servo projection system moves the image to a new location. Each 3/4-in. diameter fiber optic cable has some one million strands.[44]

Programmable Display Generator

The many displays to be integrated require a "junction box" to generate and overlay the various map, sensor, and data inputs. The Ferranti programmable display generator would be a suitable unit. It takes data from a variety of sources—navigation, weapons, communications, engine monitoring, etc.—codes the information using symbol generation, and overlays the images on the color and monochrome multifunction displays, or on the HMD. The unit is 5 × 7 × 19 in. long and weighs 15 lb. It has a 1553B interface and works at up to 1024 × 1024 resolution. A possible signal flow for our system is shown in Fig. 26.

Voice Generation and Recognition

The crew members should be able to make verbal inputs and commands to the system and receive verbal messages from it, particularly alerts. For the near term, we can specify the LSI Voice Controlled Interactive Device (VCID), a unit that has been flight tested in the F-16 and is used to initiate and control symbology on multifunction displays during combat maneuvering conditions. The system is personalized to the user's voice with a recorded solid-state cassette. The system appears to work well in high noise. The cassette receptacle is 2 × 5 × 5 in.; the data processor is 12 × 7 × 8 in. deep.

For the far term, more sophisticated voice command processors are being developed by Sanders, SCI Systems, and Bendix/Crouzet. The Crouzet system has been tested in prototype form on the Gazelle helicopter. The units allow the operator to talk directly to avionics systems without pausing between words. Eventually, it is expected that the user will be able to interrogate any of the onboard systems and ask for advice on strategy and tactics, which will then be presented verbally and graphically.

Research on combinations of speech and pictorial displays has shown that tasks that are temporal in nature or that have a specific orientation in the cockpit may be best alerted using verbal channels. Information that is spatial (maps or diagrams) or multilevel (with the user "zooming" in on the problem) is best portrayed with pictorial displays.[45]

Controls

The operators should have more or less identical sets of control devices. Except for some of the special three-man designs, each of the crew members should be able to drive, query the system status, add to the database, perform fire-control functions, and communicate with other vehicles.

[44]W. A. Demers, "Services Eye New Visual Systems," *Military Forum*, March 1988, pp. 19–21.

[45]Christopher Robinson and Ray Eberts, "Comparison of Speech and Pictorial Displays in a Cockpit Environment," *Human Factors*, 29(1), 1987, pp. 31–44.
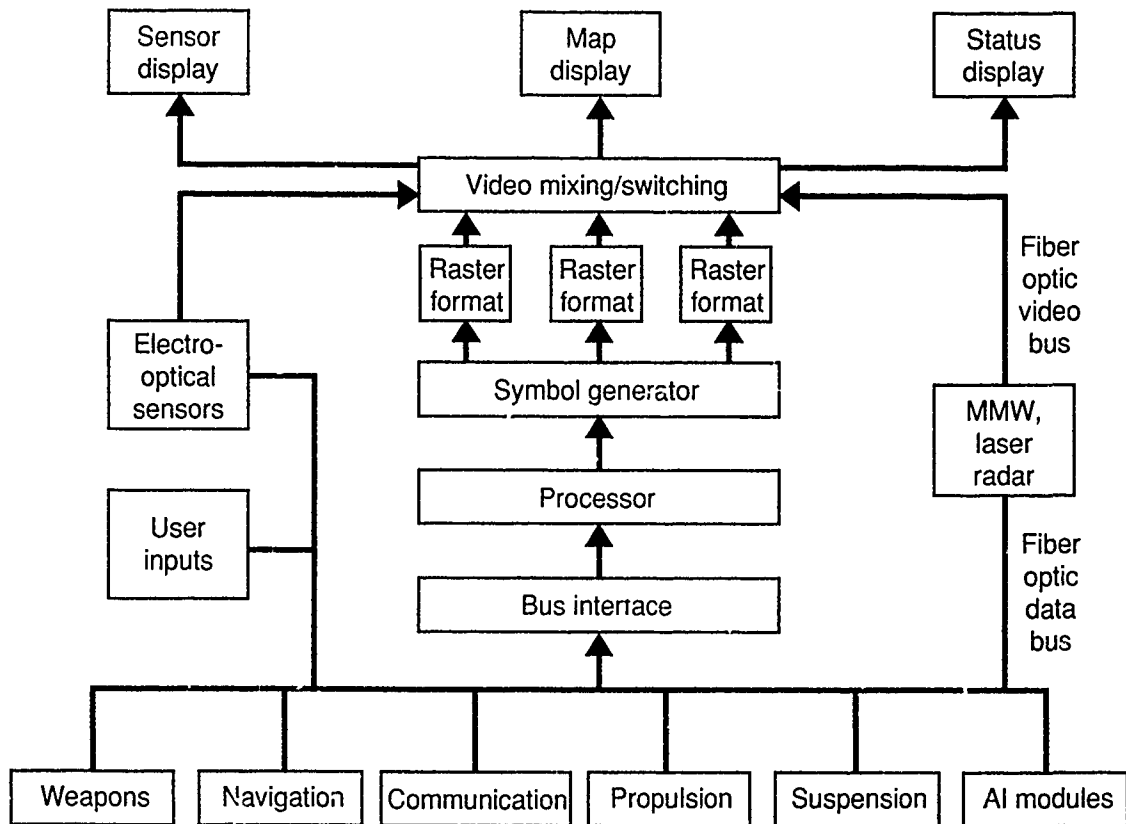
Fig. 26—Display generator signal flow

A good choice for the control grips are pairs of Measurement Systems four-axis displacement controllers. The handgrip on the sidestick controllers sits on a gimballed bearing on top of a 5 cu in. box. Up to ten optional press buttons and rocker switches can be specified, although only a few should be used. Some fighter aircraft have as many as 16 functions on the control stick and throttle,[46] but this entails massive amounts of training along with practice to maintain proficiency. The problem is that the switches must all be programmed in the pilot's memoiy and found and actuated by touch, often during moments of extreme physical and mental stress. It would appear that most of the noncritical functions should instead be activated using touchpads.

Force controllers are currently gaining favor over displacement controls on aircraft. They require less volume for movement, are less tiring for wrist muscles, are more sensitive, cannot jam, and are more reliable. Some currently available units are operational on the F-16 and Apache.

The distribution of control functions among multifunction display touchpads, control grips, keypads, and foot pedals is important. Entry of digits is generally best through a dedicated keypad. Dedicated switches are needed for emergency functions when the system is

[46]"Revolution in the Cockpit," *Aviation Week and Space Technology*, April 11, 1988, pp. 59-75.

degraded, when they have a natural location (power, fuel master), or they result in adverse reactions (emergency brake). Control sticks are best for continuous control activities and associated functions (special weapons enable switch, gun/sensor switch). Most of the rest of the control inputs for communication, navigation, sensors, and vehicle subsystems can be performed with touchpads. One rule is that no function or piece of data should be more than four switch hits from the first menu display.[47] These may be effected using conventional branching logic or with tailored logic specific to the mission phase.

In the far term, force feedback may be added to the grips, "virtual touchpads" may be generated by the HMD projection system, and high-level voice commands can be added to the voice recognition system. Force feedback would give an impression of turret rotation inertia, limit constraints, and the like. If HMDs are used in the far-term system, virtual touchpads may be projected by the visor display and activated by gloved hand sensing. Voice commands, finally, would trigger complex sequences of actions. In the Air Force Supercockpit program, for example, a single utterance of "Battle!" would result in ejection of fuel tanks, activation of bombing systems, and initiation of electronic countermeasure (ECM) operations.

Display/Control Configurations

We integrated the set of display and control components into recommended crewspace layouts, as shown in Fig. 27. The figure shows a two-man layout for the near term, with CRTs and flat panel displays providing information to the crew, the simplest and most direct approach. The left portion of the panel has the communication system, voice generation and synthesis system, and all hard switches (power on, emergency controls, etc.). The two center CRTs show a horizontal map display and perspective displays from the sensors. The right display is a flat panel system status monitor. It shows diagnostic information, system stores, database responses, and other textual information. All of the displays have integrated touchscreens with programmable legends. Alphanumeric entries are made through a keyboard on the console beneath the screens. Control of the pan, zoom, and cursor are made through the touchpads and the right joystick.

The far-term two-man system is similar, except that many of the functions are assumed by a helmet-mounted display. The sensor display is projected on the helmet visor, with panning control made through head (and possibly eye) movements. The CRTs previously showing sensor and map displays would be full color flat panel displays, and the one showing sensor displays would show auxiliary views, such as target zooms, reverse direction, and secondary sensors.

It should be apparent that our system designs concentrate on hatch-closed operations. The sensors, displays, controls, and crewspace configurations all focus on achieving effective remote driving, search, and target engagement performance. Only in safe march or rear area operations can the crew count on open-hatch conditions, without danger of beam weapons, NBC, fragments, small arms fire, or other disabling threats. Normal environmental obscuration from fog and dust can often make out-the-hatch viewing ineffective. General Dynamics

---

[47]G. L. Calhoun, "Control Logic Design Criteria for Multifunction Switching Devices," *Proceedings of the 22nd Human Factors Society Meeting*, 1980.
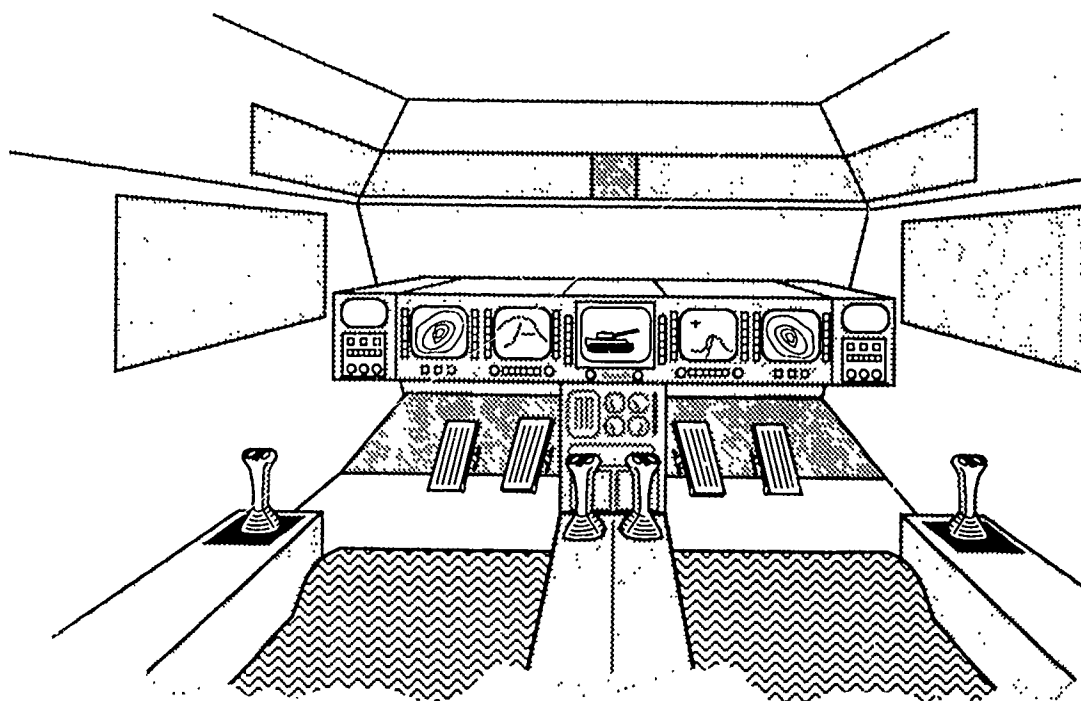
Fig. 27—Integrated two-man crewspace layout

Land Systems tests with periscopes, CRT displays, and HMDs in driving and search tasks found that the operators could effectively drive a light armored vehicle with CRTs and HMDs, reaching speeds of up to 45 mph on a rough track.[48]

AIDING AND AUTOMATION SOFTWARE

The descriptions of sensor packages, signal processing algorithms, and display and control configurations all highlight the need for extensive onboard aiding and automation. The operators cannot simply view all the incoming information, decide if there is a threat, and respond accordingly. They need help in situation assessment, sensor control, and many other activities. These functions should not be performed by separate, stand-alone modules. Instead, we envision a set of loosely coupled artificial intelligence (AI) modules for aiding (where AI is defined as having some interpretation or planning capability, which may be achieved by rules, search procedures, dynamic programming techniques, or other methods). The AI modules would interface through a fast network and all access a common situation database. We explored many relevant aspects using our RISE (RAND Integrated Simulation Environment) system, as described in the simulation section.

---

[48]Interview with GDLS personnel.

AI Modules

Virtually all of the functions onboard the armored platforms will be automated to some extent. This will be true of both the two-man and three-man versions, and of the light and heavy vehicle configurations. The crew members will perform many of the recognition, planning, and continuous control functions, with the automated system taking over portions of such tasks as communication management, sensor control, target tracking, target prioritization, fire control, maintenance and supply checks, and fault diagnosis. In the time frame considered, we do not expect that reliable systems will be available for automated driving, machine vision, damage reconfiguration, or full natural language processing. The automated systems will also not attempt any forms of learning: they will not autonomously adjust their behavior in response to positive or negative outcomes. Instead, they will follow consistent behaviors for aiding and automation.

We have specified structures and behaviors for eight AI modules:

- Navigation Aids
- Situation Report and Assessment
- Command and Control
- Target Acquisition and Engagement
- Security Status
- Power Distribution and Conditioning
- Maintenance and Supply Status
- System Control (man-machine interface)

Detailed input-output descriptions are given in App. A for each of the modules. Prototype rules and planning procedures for the first four modules have been implemented in RISE, as described in App B. Below, we give brief descriptions of each module's functions.

The first module, Navigation Aids, helps the crew members in driving and mission planning. Using inputs from the communication system, the onboard terrain model, and the plan database, the system produces an annotated map display. This display shows terrain features, enemy and friendly forces, and movement plans. It also performs route planning and makes deployment recommendations, taking into account intervisibility considerations and terrain characteristics. In emergencies, it can take over driving functions for short distances, moving the vehicle between firing positions (over a previously observed, manually driven course).

The Situation Report and Assessment module makes inferences about enemy position, tactics, and knowledge (such as what the enemy knows about the vehicle's own status). Scanning the onboard database, the module also draws conclusions about the status of friendly vehicles and of the communication network. Most of the inferences are made using rules and schema.

The Command and Control module handles the generation, transmission, receipt, and interpretation of messages. It also maintains a communication table enumerating the status of point-to-point links, updating the table whenever a communication is received. The mes-

sages themselves may be data, queries, commands, or acknowledgments. All are entered into the situation database, and some will trigger further actions. Outgoing messages are checked to make sure that the information value exceeds the transmission costs.

Target Acquisition and Engagement is the most complex of the eight modules. This module checks the situation estimate, processes raw sensor data, inputs intelligence information, checks support status, and recommends intelligence gathering and engagement actions. The functions range from changing sensor settings to performing automatic target recognition. In certain instances, the module may run simulations of the expected enemy and friendly actions, and evaluate the projected outcomes.

The Security Status module senses area intruders near the vehicle and alerts the operators to any likely threats. It is used primarily during nonengagement periods, because the system uses the standard suite of sensors—TV, FLIR, and MMW radar. It also uses ATR routines to identify suspicious contacts.

Power Distribution and Conditioning monitors and adjusts for the power demands of the vehicle subsystems—turret drive, autoloader, electronics, NBC system, etc. It prioritizes demands and automatically apportions power, subject to operator override.

The Maintenance and Supply Status module checks the vehicle subsystems, alerting the operators and follow-up maintenance supply groups of any deficiencies. The module initiates emergency responses to fire and smoke detections, activating the onboard fire suppression system. It also aids in fault diagnosis.

System Control, finally, orchestrates the activation of the other modules and acts as an intermediary between them and the user. It reconfigures controls and displays according to the mission phase. In the far-term system, it may even apportion tasks between the automated systems and the crew members, relieving the humans of excessive workloads.

The AI modules will result in many new display functions. They will overlay maps on the displays, show the command and control situation, animate mission plans, and answer a variety of questions. Some of the more important questions the system might answer are:

- Show best intercept point (sensor and map displays)
- Show best ambush location (sensor and map displays)
- Show best cover positions (sensor and map displays)
- Show coordination with friendlies (map display)
- Show intervisibility of enemy and friendlies (map display)
- Show chances for multiple shots (status, map displays)
- Show zones of fire (perspective and map displays)
- Show likelihood of detection (map display)
- Show auto sentry status and security situation (map display)
- Show maintenance needs (status display)

Presentation of this information will require special procedures for window formatting, decluttering, object highlighting, and touch panel reconfiguration. The system may have to synthesize full three-dimensional views from the terrain database.

Automatic Target Recognition (Far Term)

Automatic Target Recognition (ATR)—automatic computer-based scanning and interpretation of images—is a dynamic new area of development. The most sophisticated and powerful of the ATR systems in development appears to be the Honeywell Imaging Sensor Autoprocessor (ISA), an outgrowth of the PATS II experimental system. The ISA system uses a highly parallel scene processor, with a mixture of statistical and heuristic models. Operating at 3–4 billions of operations per sec (BOPS) (most experts feel that 5–10 BOPS are the minimum needed to have acceptable sensitivity and low false alarm rates), it can coprocess data from up to three sensors simultaneously. The unit has four functions in one box: video multiplexer, segmentation processor, recognition processor, and execution controller. Like Martin Marietta's similar GAPP processor, the ISA unit's space claim is less than 1 cu ft. Other developers of ATR technology include TI, Hughes, Westinghouse, and RCA.

For ATRs to work, the sensor inputs will have to be very good. Standard Advanced Infrared Sensors and other new FLIR systems are expected to provide resolution in the 0.05 to 0.1 mrad range. This will, under perfect conditions, produce 0.2-m-sized pixels at 4 km, which just satisfies the criteria for recognition (12 to 20 pixels or 6 to 10 cycles of spatial resolution across a 2.4-m-high target). This assumes sufficient target contrast, which may not be present due to smoke, fog, dust, foliage, or surface treatments. If the sensor platform is moving, it also assumes sensor stabilization at least to the level of resolution. If multiple sensors are used, frame registration errors must be held to about 0.02 mrad. DC signal restoration may be necessary to improve frame-to-frame repeatability. Finally, fiber optic cable bandwidth of at least 50 MHz will be needed to handle each video signal.

The ATR system works by looking at the image and moving a pair of small concentric windows over it. Parallel processing operations then check for potential targets of the right contrast and size, segment the candidate targets using edge operators, and attempt to fit templates and features to the remaining candidates. Detection probability has become relatively good for some systems, but false alarms remain a major problem. The eventual goals for the Honeywell ISA system are 90 percent detection probability and 90 percent correct classification.

For the near term, limited automatic search, acquisition, and tracking of targets can be provided by the Northrup TISEO system or the PNVS tracker. Both are fielded (TISEO is operational on the F-14A), although they are used only for air targets without ground clutter. The normal input is day TV. Automatic cueing alone may be accomplished with the TI AUTOCUE system. This unit does not track targets frame-to-frame, but it is optimized with respect to ground targets. A similar unit appears to be in the sensor module for the LTV hypervelocity missile system. The unit is supposed to be able to track up to three targets simultaneously. Auto detection and tracking systems are also under development for the M1-A1 improvement program and the Elevated Target Acquisition System (ESAT).

We may evolve through several levels of ATR aiding as systems become more proficient. At the lowest level, ATR provides cues that direct the operator's attention to possible targets. Developed further, it can detect and present tentative targets for evaluation and decision by the operator—aided target recognition. One version lines up enlarged images of targets at

the top of the screen, labeling them with respect to priority. Progressing further, the ATR system can recognize and prioritize targets for attack without human assistance—automatic target recognition. In an ultimate form, it could even fire weapons without attention by the crew.

The mix of sensors needed for ATR depends on the types of targets and levels of obscuration present. Passive sensors excel in recognizing combinations of high-temperature signatures and threat-like shapes, whereas active sensors (MMW radar, laser radar) isolate high doppler signatures (rotor blades) and antennas (from distinctive glint). An active/passive combination gives more signature dimensions for ATR algorithms and makes ATR more robust against reactive threats, but does result in additional hazards from detection and homing.

ELECTRONICS PACKAGING

The set of equipment required onboard an armored vehicle (MBT, Bradley, or LAV) includes the sensors, communication systems, displays, and controls described earlier along with such support and integration items as computer processors, graphics drivers, militarized disk storage, digital bus network, and environmental control. We next describe the additional integrating elements and suggest a packaging configuration.

Microprocessors

The many functions of aiding and automation are estimated to require some 9–12 millions of instructions per sec (MIPS) of power in the near term, and 30–40 MIPS in the far term (see App. A for module-by-module breakdowns of processor requirements). We also noted earlier that the far-term system will require additional special purpose parallel ATR processing of some 6–10 BOPS, along with a dedicated graphics engine. At the minimum, the near-term system will require three Computing Devices 32-bit, 16-MHz, 3–4 MIPS, milspec, MC68020 processors, each with 6 Mbytes random access memory (RAM). They will be programmed in ADA language (although some of the graphics routines may have to be in C). Presumably, the processor architecture will conform to the upcoming MIL-STD 32-bit instruction set architecture standard. Each processor is mounted on two 6 × 10 in. cards. The entire unit, including power supplies, should be roughly 2 cu ft.

An alternative for the near term might be the Loral milspec Shark computer. The single board RISC processor achieves 10 MIPS and runs under UNIX, supporting ADA, C, and Fortran, and connecting to most networks. In a double ATR package (again about 2 cu ft), it houses a 170 Mbyte Winchester disk and up to 64 Mbytes of internal memory.

Another alternative is Control Data's 32-bit MVP (Modular VHSIC Processor), designed for C^3I applications. This phase 1 VHSIC system is a networked set of processors running at 50–100 MIPS. One 6 MIPS processor and 32 Mbytes of memory can be accommodated in one ATR box weighing 16.5 kg. Even faster and more nuclear hardened architectures are expected in the next decade with MIMIC (Microwave/Millimeter-wave monolithic Integrated Circuit) systems using gallium arsenide (GaAs) components. A far-term system might be

Prisma's GaAs version of the Sun 4 RISC processor. This unit is supposed to run at 250 MHz, producing 250 MIPS and having 256 Mbytes of internal memory. The unit is claimed to fit into a space about the size of a two-drawer filing cabinet, and draw 5 kw of power. If a ruggedized, miniaturized version could be produced, this processor could handle all the computation, graphics, and database functions envisioned for even a command version of the RCV, although ATR would still require a dedicated processor.

In the near term, terrain modeling may be performed with a custom set of routines derived from our experiences with the RISE and JANUS systems. The capabilities will be similar to those of the Hughes ITARS (Integrated Terrain Access and Retrieval System), but will be much more interactive. To display 2-D and 3-D maps in real time (a far-term goal), we will need the equivalent of a Chromatics CX 1536 high-resolution color graphic display system. This GKS-based display system can calculate 500,000 graphics vectors per sec and supports a wide variety of input and output devices. We have used a version of this system in some of our RISE work (see Sec. IV).

Mass Storage

We will need a lot of disk space for terrain, state, and program data. Two 160-Mbyte Control Data MADS (Military Advanced Disk System) milspec formatted hard disks should be sufficient for the near term. These disks will be fully redundant. Each five-platter disk will be able to store all necessary vehicle and AI module information. The Control Data units have been tested against tank shock and vibration standards (there is a "park heads" command when the main gun fires). Each unit is roughly 1/2 cu ft. Larger 5–1/4 in. milspec disk drives from Miltope offer up to 688 Mbytes per spindle.

If highly detailed maps are found necessary (say down to 1–2 meter resolution), we may need to specify MAPS (Mission Analysis and Planning System) by Fairchild Communication and Electronics. MAPS can store more than 300 Mbytes on each 5–1/4 in. optical disk.

Data Bus

To pass video, map, and command data, we will need a much higher-speed data bus than the current 1553B wire version. Even the MIL-STD-1773B fiber optic version of 1553B is too slow and has too short a message length (32 16-bit words) for our applications. The best choice now in development appears to be a dual redundant Collins 50 megabit/sec high-speed fiber optic data bus. This unit, comprising a bus controller and network, should occupy roughly 1 cu ft.

Power Bus

Parallel to the data bus, the vehicles will have a power distribution network. The turret motors will have to have high accelerations and slewing rates to track and engage low-flying aircraft. Twenty-eight volt direct current (VDC) motors allow traverse speeds on the order of 60 deg/sec and elevation accelerations of 4 mils/sec.[2] Size reduction has favored new trends

toward high-voltage motors.[49] In the far term, it may be necessary to incorporate a separate 270 VDC circuit for the turret motors.

Environmental Control

The armored vehicles will have an integrated heating and cooling system, handling everything from electronic module cooling to crew compartment temperature regulation. The vehicle will also have an integrated positive pressure NBC system. Two modes of temperature control for the crew are envisioned. The first is a closed-hatch circulation system, in which the users can set temperatures for fatigues or for full-coverage suits. The second mode is in open-hatch or system damage conditions. The operators may then have temperature-controlled NBC suits and helmets (an example is the liquid-cooled garment produced by Life Support Systems, Inc., now in testing with Canadian and Israeli tank crews). Eyepieces, displays, and touch panel keys will have to be compatible with helmet faceplates and thermal gloves.

The NBC system specified for the M1-A1 block II upgrade should be more than sufficient for the near-term MBT. The configuration will have to be modified to allow movement from the sponson area to a region at the feet of the crew members. The unit may also be downsized, because it will be conditioning a much smaller space in the forward crew compartment than the large M1 internal volume, which includes most of the chassis and turret.

The use of compartmentalized crew, gun, and propulsion systems reduces one current problem. Designers normally assume that the main weapon cannot be fired or a new round chambered under NBC conditions, because the fume extraction flow rate is necessarily much higher than the NBC overpressure system can handle. This problem is not present with isolated crew and weapon compartments. However, if a jam or other weapon system problem occurs under contaminated conditions, the crew will have to don protective gear and work as best it can. More likely, the vehicle will have to fall back and be repaired by special support groups.

A special problem related to NBC is vulnerability to microwave beam weapons. The vehicle may be subjected to 1–10 GHz microwave radiation. Humans may become disabled after exposure of 0.1–1 watts/cm^2, whereas electronics may be damaged by 10–100 watts/cm^2. The main entry points are the hatches, blow-off panels, sensor windows, and engine access doors. Solutions are braided cabling, sensor window grids, and metal fingers for sealing hatches.

Electronics Space Claims

Table 6 summarizes estimates of volumes and weights for the near- and far-term electronic components. The volumes are for internal space, not external mast or chassis mountings. A set for a two-man crew is specified, although a three-man complement would be only slightly larger. For the near-term components, these values are soft estimates taken from currently available or developmental systems. The far-term entries are primarily extrapola-

---

[49]Jacques Lenaerts, "Design Criteria for AIFV Turrets," *Military Technology*, March 1988, pp. 16–24.

Table 6

ELECTRONICS SPACE CLAIMS

Item	Approximate Volume (ft^3)	Approximate Weight (lb)
Near-Term Components		
LLLTV	0.28	16
Day TV	0.22	20
Mini-FLIR	0.15	25
CITV FLIR	1.0	44
Digital scan converter	0.1	6
Panoramic periscope	0.5	68
Laser/radar warning	0.25	30
Acoustic sensors	0.2	25
SINCGARS	0.5	13
POSNAV	0.1	20
Sensor stabilization	0.1	10
CRT displays (4)	2.4	144
Flat panel display	0.1	5
Generator	0.4	15
Voice generation/recognition	0.3	15
Main computer	2.0	100
Disk system	1.0	40
Data bus	0.8	20
Power bus	0.5	50
Far-Term Components		
SAIRS FLIR	1.0	50
MMW radar	1.0	60
Laser radar	1.4	35
EPLRS	0.7	40
HMD (2)	0.5	20
Auto target recognition	1.0	30
Graphics engine	1.2	35

tions of developmental systems. The numbers should be treated as rough estimates due to rapid technical developments.

In sum, the near term system requires approximately 8–10 cu ft of electronics space and 4–5 cu ft of display/control space. The weight of these electronics components is a fairly minor portion of the vehicle weight, less than 300 kg. The far-term system would add 3–4 cu ft to the internal volume, along with several hundred kg of weight. For sizing estimates in the designs in Secs. IV and V, we will consider each crew station, including crew member, seat, displays, controls, hatch motors, and stores, to be approximately 400 kg.

IV. MAIN BATTLE TANK CONFIGURATIONS

INTRODUCTION

We have postulated a variety of two-man and three-man designs for a near-term future MBT. The designs feature remote guns, autoloaders, telescopic sensor masts, and other technological innovations. Generally, we found these choices to be necessary for meeting the future threat while maintaining or improving the mobility, range, and fightability of current MBTs.

In all our designs, we held certain criteria constant for comparability. All the designs use 95th percentile (a term of body size) crew members and to the degree possible, all achieve the same armor protection levels and have the same armament, propulsion, suspension, and electronics. The designs differ primarily in the number of crew, members, and their location. As a result, the designs have marked variations in projected weights, dimensions, performance, and ergonomics.

We begin Sec. IV by describing the baseline components—drive train, weapon, sensors, and so forth—in all our MBT designs. They derive from the near-term recommendations outlined in Sec. III. We then move to some critical issues: What configuration of crew, weapon, and engine results in the best performance and protection levels? What advantages and difficulties accrue from use of two-man and three-man crews?

We then present four MBT configurations. The first is a remote gun design with two men in the hull. It is something of a baseline system, since it is the smallest, lightest, and least complex of the designs. The second expands to include three men in the hull, with two variants—crew abreast and crew staggered. The third design places two men in the hull and one behind the turret, still with a remote gun. The last is a more conventional manned turret design, with a driver in the hull and two crewmen in the turret.

BASELINE MBT SYSTEMS CHOICES

As mentioned above, all of our MBT designs share similar armor protection, weapon systems, propulsion, suspension, and electronics. We will describe each of the choices made.

Armor in our designs is primarily for crew protection. Examination of the threat has resulted in specifying a protection level of 1300 mm of line-of-sight armor over a 71 deg frontal arc and down to a 38 cm lower glacis line (see Table 7 for a summary of armor specifications).

Unmanned turrets (crew-in-hull) are protected by 1300 mm of armor over a 0 deg frontal arc, whereas manned turrets are protected at the same level as manned hulls—1300 mm over 71 deg. Engine, ammunition, and fuel are given flank protection of at least 150 mm, belly armor is 80 mm beneath the crew, and top attack protection is 50 mm. Most of the armors are composite in nature, with mass and space efficiencies matching the design volumes specified. The designs assume that reactive armor will be employed.

Table 7

REQUIRED MBT ARMOR THICKNESSES

Section	Crew-in-Hull (mm)	Crew-in-Turret (mm)	Notes
Crew compartment			
Upper glacis	1300	1300	High E_m, low E_s defeat heavy CE[a]
Lower glacis	700	700	
Upper skirt	400	630	400 mm uses high E_s, low E_m to equal 630 mm
Lower skirt	120	120	
Top	50	50	Additional protection provided by gun block
Bottom	80	80	
Turret			
Front	1300	1300	
Sides	290	630	290 mm defeats medium ATGMs in flank
Back	40	40	
Top	50	50	Designed to deflect small shaped charge warheads
Noncrew hull/turret			
Sponsons	290	290	Defeats medium CE and KE in flank
Lower skirt	120	120	
Top	50	50	
Back	40	40	Except grille areas
Bottom	20	20	

[a]E_m is mass efficiency and E_s is space efficiency.

A large (135-mm) solid propellent gun is used as the main gun in all designs. The primary round is a long rod penetrator loaded in two pieces by a carousel or bustle autoloader. At least 35 two-piece cannisters are carried, in a mix of 28 2-m KE rounds and 14 1-m CE rounds, for a total of 42 rounds. The gun has a −10 to +20 deg nominal elevation range, with a sealed compartment in the roof accommodating the gun in 10 deg depression. The crew also has a 7.62 coax machine gun for soft targets and antipersonnel operations.

Mobility is provided by an AIPS (Advanced Integrated Propulsion System) package. We are using the 1500-hp turbine version of this engine/transmission/cooling package, which should displace a similar volume and produce about the same horsepower as the alternate diesel AIPS. At least 330 gallons of fuel storage are specified in each of our designs, resulting in roughly one and a half battle-days of operation. A hydropneumatic suspension system is employed, in combination with modern double-pin tracks. Space is also allocated for a pump and 50 gallons of hydraulic fluid.

A special NBC system is fitted forward of the crew compartments, along with a dedicated compressor/generator. The overpressure system is sized differently for the different crew configurations. The system also provides air conditioning for the crew and electronic components.

The sensor package is quite extensive. All designs have two sensor masts, each of which has a color video camera, FLIR, laser rangefinder, and acoustic sensors. The two masts in this design can be operated independently by the various crew members, or the users can hand off contacts and targets. Normally, the mast with the mini-FLIR will be used for search, driving, and secondary targeting. The other mast (with the more powerful CITV FLIR) will be used primarily for target tracking, identification, and fire control. The mast sensors will be connected to chassis electronics using flexible fiber optic cables. On the front and rear of the chassis, the vehicles have LLLTVs and laser-radar warning devices. Optionally, a MMW radar may be mounted over the gun armor, using a flip-up antenna similar to that used on STARTLE. There may also be a back-up panoramic sight head on the front glacis. The hatches are the lift-and-swing-away design, with armored visors.

The crewspace has CRTs and flat panel displays in this near-term set of designs. We are assuming use of SINCGARS communication, a POSNAV system, a voice generation and recognition module, and dual control grips. Associated electronics (main processor, mass storage, bus network, etc.) in the over-sponson areas take up roughly 10 cu ft of additional volume.

In all the designs, great efforts were made to compartmentalize the crewspace, ammunition, fuel, and engine areas of the vehicle. For example, the crew and ammunition compartments are separated by a 35-mm thick protective bulkhead. Although this reduces accessibility of some components by the crew, it greatly increases survivability in the event of a hit. The various designs differ primarily in their crewspace layouts, and as will be apparent in the designs presented, have widely varying levels of operator visibility, orientation, access, and coordination.

MAJOR DESIGN CHOICES FOR AN ADVANCED MBT

Front Crew, Rear Engine Configuration

For each of our MBT designs, we chose a front crew module and rear engine configuration. Most of the heavy armor is placed forward of the crew, with the heaviest skirts extending the length of the crew compartment. A front crew design places the crew positions somewhat under the gun overhang and upper glacis, giving a measure of top protection. The forward crew has some advantages in driving effectiveness and target search, because the crew has less obscuration from the chassis. Rear engine position facilitates engine maintenance and replacement, and allows direct venting of exhaust at the rear, minimizing an IR signature. Placing the gun and autoloader in the center of the vehicle also helps to reduce firing torques. Finally, a front crew with heavy armor is balanced to some extent by the rear engine, transmission, ammunition, and fuel.

The rationale often cited for front engine placement is that it greatly contributes to protection. However, if one were to assume equal armor mass for front and rear engine designs, our analyses show that front engine designs frequently offer less protection. Similarly, for

equal protection, front engine designs may result in a higher armor mass than their rear engine counterparts.

In Fig. 28, a crew compartment of length L_c is shown. Components of density r_b are placed directly ahead of the crew in a compartment of length L_b. The frontal armor is of length L_a, and the side armor is defined by a combination of penetration distance (P), the frontal arc, and L_b. Note that $P > L_a$, because we are assuming the frontal armor thickness may be reduced in direct proportion to the protection provided by the components.

In our analysis, we assume that space efficiency $E_s = 1$ and mass efficiency $E_m = 2$ for the armor, and that $E_m = 1$ for the components. We also assume that the components are homogeneously distributed. Armor mass may then be plotted (Fig. 29) as a function of L_a and P_b/P_a, the density ratio. We note that as the density ratio decreases, armor mass increases for any component length. Because a modern engine would exhibit at most a density ratio of 0.2, placing the engine ahead of the crew would in general increase the armor mass of the vehicle. This behavior is caused by the growth in the skirt length as either the density ratio decreases or the compartment length increases. The analysis does not address the case in which the engine is forward and to the side of the crew. Such a tandem crew-in-hull configuration was not considered due to difficulties of coordination, armoring, and vehicle length.

Two-Man and Three-Man Crews

Over the years, a wide range of crew complements have been used or proposed for tanks. The designs range from completely unmanned vehicles (autonomous or controlled bysupervisors) to four-man tanks such as the Israeli Merkava, which can also carry up to five infantrymen along with the crew. As automation has become available, crew reductions have shown up in all types of fighting vehicles—helicopters, fixed wing aircraft, artillery, armored vehicles, and other systems. Advantages in size, weight, protection, and cost can all result from vehicle crew reductions, although some of the functions normally carried out by the onboard crew may be relegated to support groups (e.g., repair, maintenance, and replenishment).

The first man to be automated out of the traditional four-man crew is, of course, the loader. Upgunning the weapon from 120 mm to 125 mm and beyond makes manual loading impractical anyway, due to the weight of the rounds or use of two-piece ammunition. Autoloaders have been incorporated in several existing tanks, such as the Swedish S-tank and the Soviet T-64, T-72, and T-80, and they are planned for many future tanks, among them the French LeClerc and Japanese TK-X.[1]

The remaining tasks for the crew—driving, navigation, communication, fire control, emergency response—can be divided among two or three crew members. We do not consider one-man tanks to be viable in this time frame because of the wide range of coordinated tasks and the psychological isolation. Even in combat aircraft, the trend is not always toward single-seat configurations.[2]

---

[1]Kensuke Ebate, "Japan's New TK-X Main Battle Tank: Initial Impressions," *International Defense Review,* June 1988, pp. 655–658.

[2]Bill Sweetman, "Challenges for the One-man Cockpit in the ATF," *International Defense Review,* May 1985, pp. 687–689.
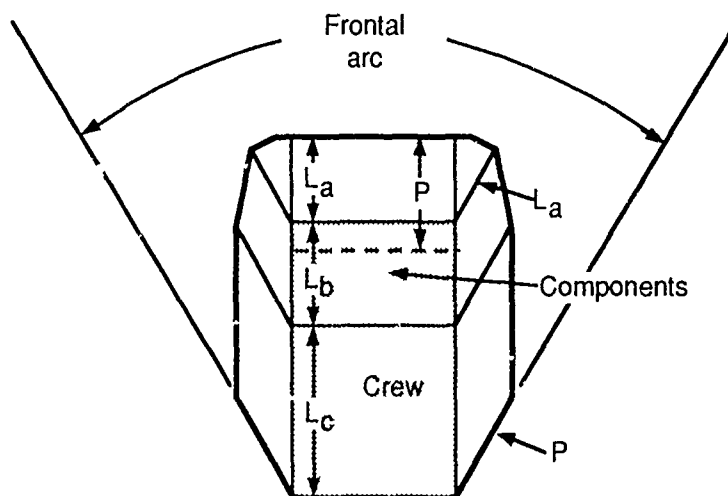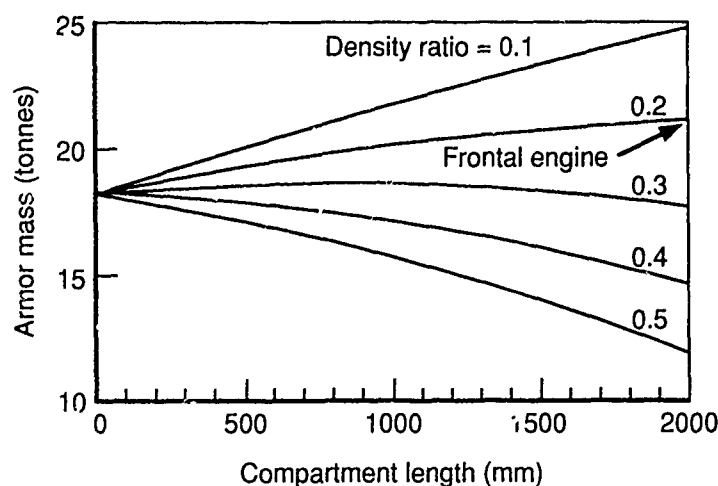
Fig. 28—Components as frontal armor

Fig. 29—Effect on armor mass of front engine configuration

With tanks, virtually all normal functions can be accomplished by a crew of two, including searching multiple sectors, firing on the move, and communicating while performing other functions. The places where three crew members become important are in emergency responses, maintenance functions, and round-the-clock operations.

For example, a three-man crew may be able to perform some activities that a two-man crew would have difficulty with (using current technology). Three crew members may be able to fire on the move with both the main gun and secondary armaments. They should be able to search, fire, and communicate at the same time. They may be able to engage and perform damage control. They should be able to search a wider area than a two-man crew, perform damage assessment more accurately, and operate more effectively under degraded conditions (smoke, NBC, rain, etc.). Some writers claim that a three-man crew is essential for

firing on the move—a driver for maneuvering around obstacles, a gunner to engage targets, and a commander to exercise all-around vision and overall control.[3] Some of these functions, of course, may be aided through the use of automated navigation, communication, target acquisition, and engagement systems. Appendix A describes many of these technologies and their expected capabilities.

Three-man crews should also be able to operate over longer periods of combat than a two-man crew, with the three crew members alternating two man shifts. Two-man crews can be relieved on the battlefield by fresh crews, as in the planned German two-man tank concept. However, the replacement crew requires a special vehicle to move up to the tank, and there are serious doubts about the effectiveness of such a rendezvous under confused battlefield conditions.

As we will see in the design layouts, the main disadvantages of three-man crews are increases in vehicle size, loss of some top attack protection, and increased equipment expenditures for displays, controls, NBC units, and other items.

CANDIDATE MBT DESIGNS

We next present four detailed MBT designs. The first is a baseline two-man design, with the men seated abreast in the hull. The other designs are all three-man excursions from this baseline, sharing most of the same components but differing in crew position and responsibilities. We will attempt to compare the various designs in terms of projected performance, weight, and size.

Two-Man Remote Turret Concept

The two-man remote turret design has been the focus of much of our efforts, and is something of a baseline for developing the several other excursions. It is the smallest and lightest of the designs explored, because the in-hull two-man crew configuration presents the smallest volume for full armor protection.

Figures 30 through 33 show layouts and a perspective rendering of the two-man MBT. The two crew members are each provided some 28 in. of shoulder spacing, and are able to view their displays in either hatch-closed or hatch-open modes. Being side-by-side, they can coordinate verbally or by pointing at each other's displays. Each can perform all major functions—search, tracking, engagement, driving, and so on. The crew compartment is somewhat confined, however, leaving little room for personal articles, rations, or hygiene. Ingress/egress is straightforward, with the crew able to swing the hatches to the side and pass through even when the gun is overhead. In extreme emergencies (hatches damaged, or under direct fire), the crew can exit through a counterweighted floor hatch under one of the seats.

Some special crewspace design choices were made with the two-man configuration. The spall liners on the sides of the crew compartment are cut out in some areas to accommodate

---

[3]Robin Fletcher, "Main Battle Tank Crew Reduction," *International Defense Review*, Vol. 1, 1987, pp. 69–73.
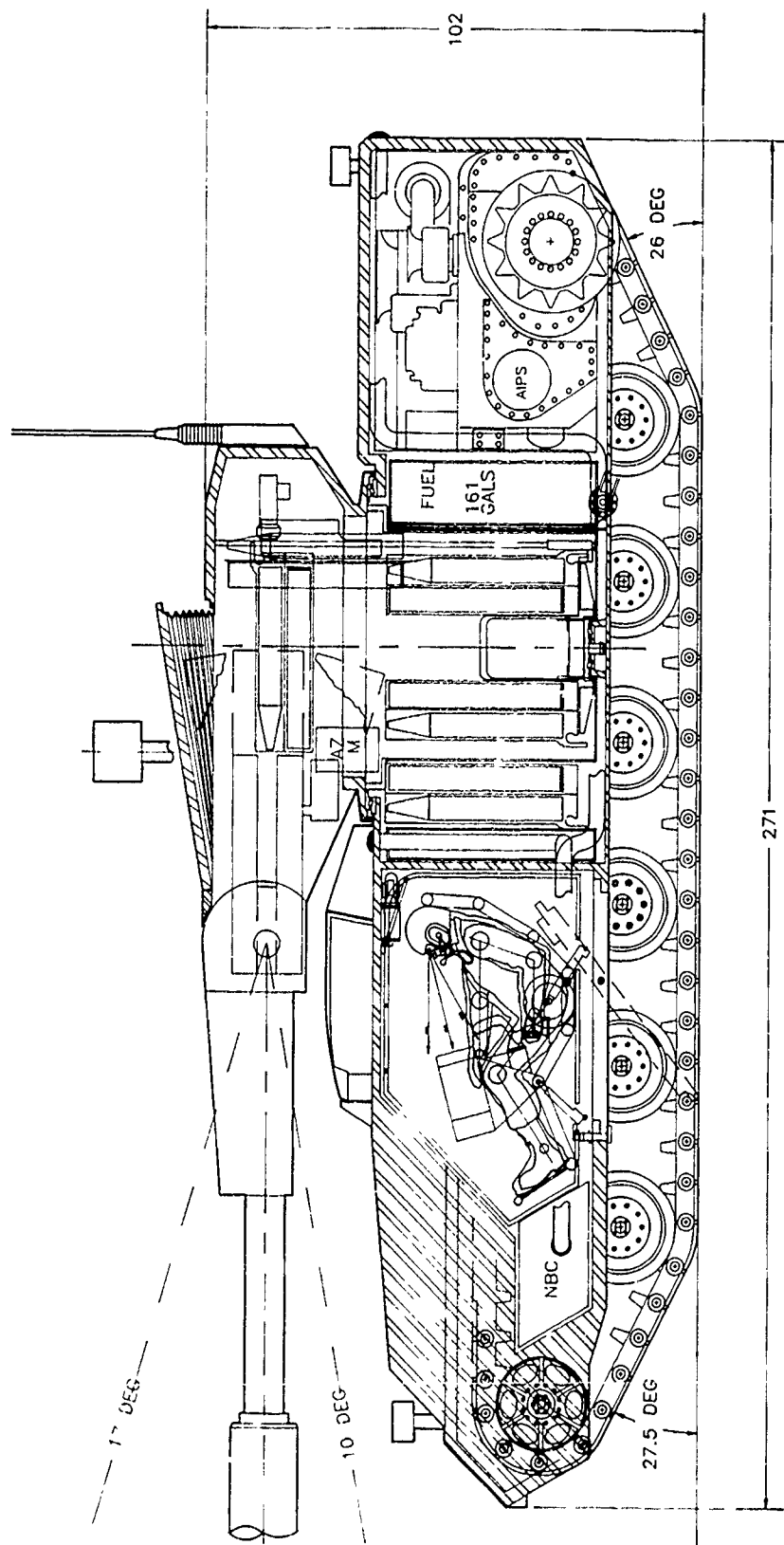
Fig. 30—Two-man remote turret design: side view

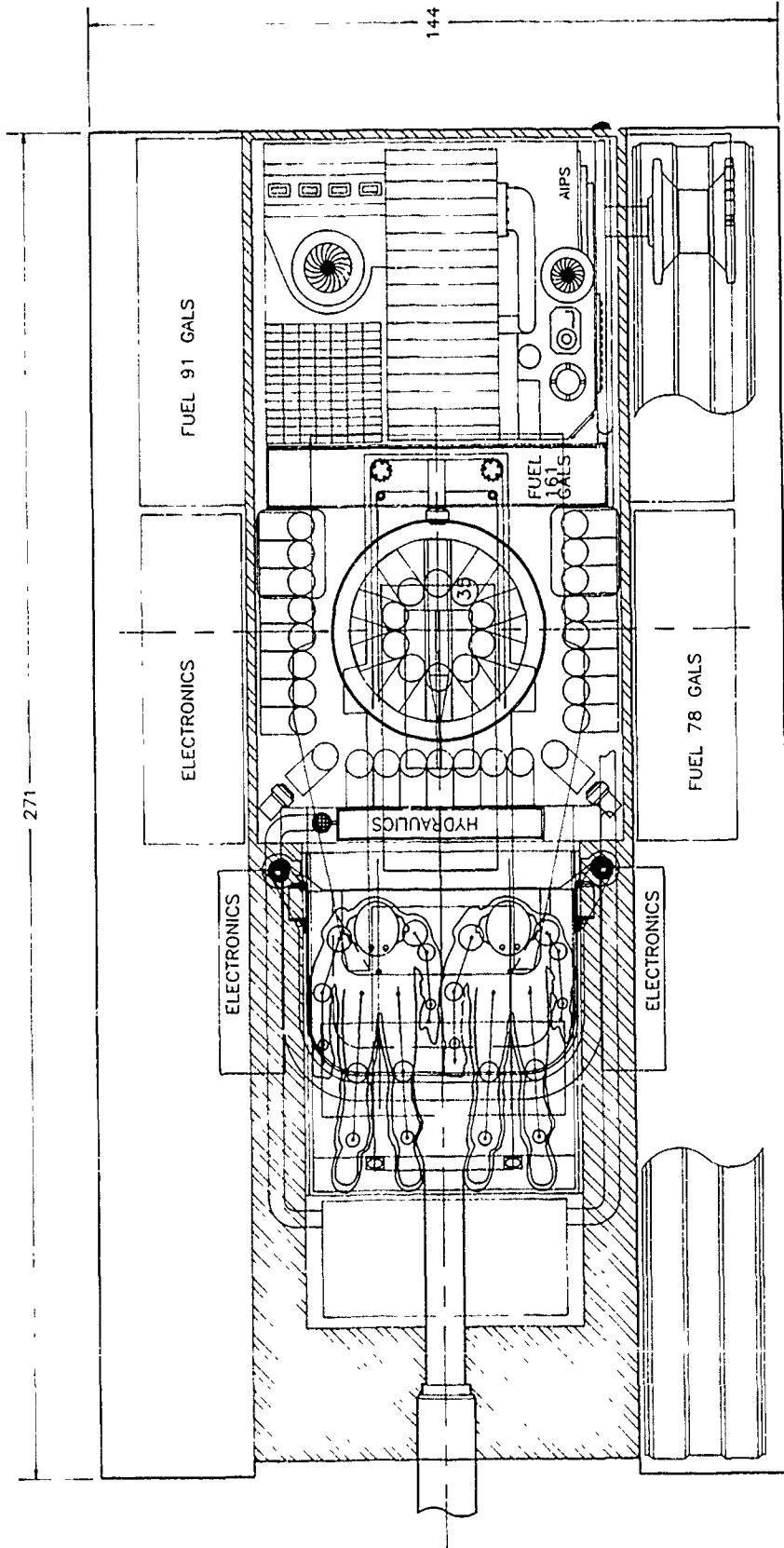Fig. 31—Two-man remote turret design: top view

ELECTRONICS

ELECTRONICS

EL M

EL M

ELECTRONICS

ELECTRONICS
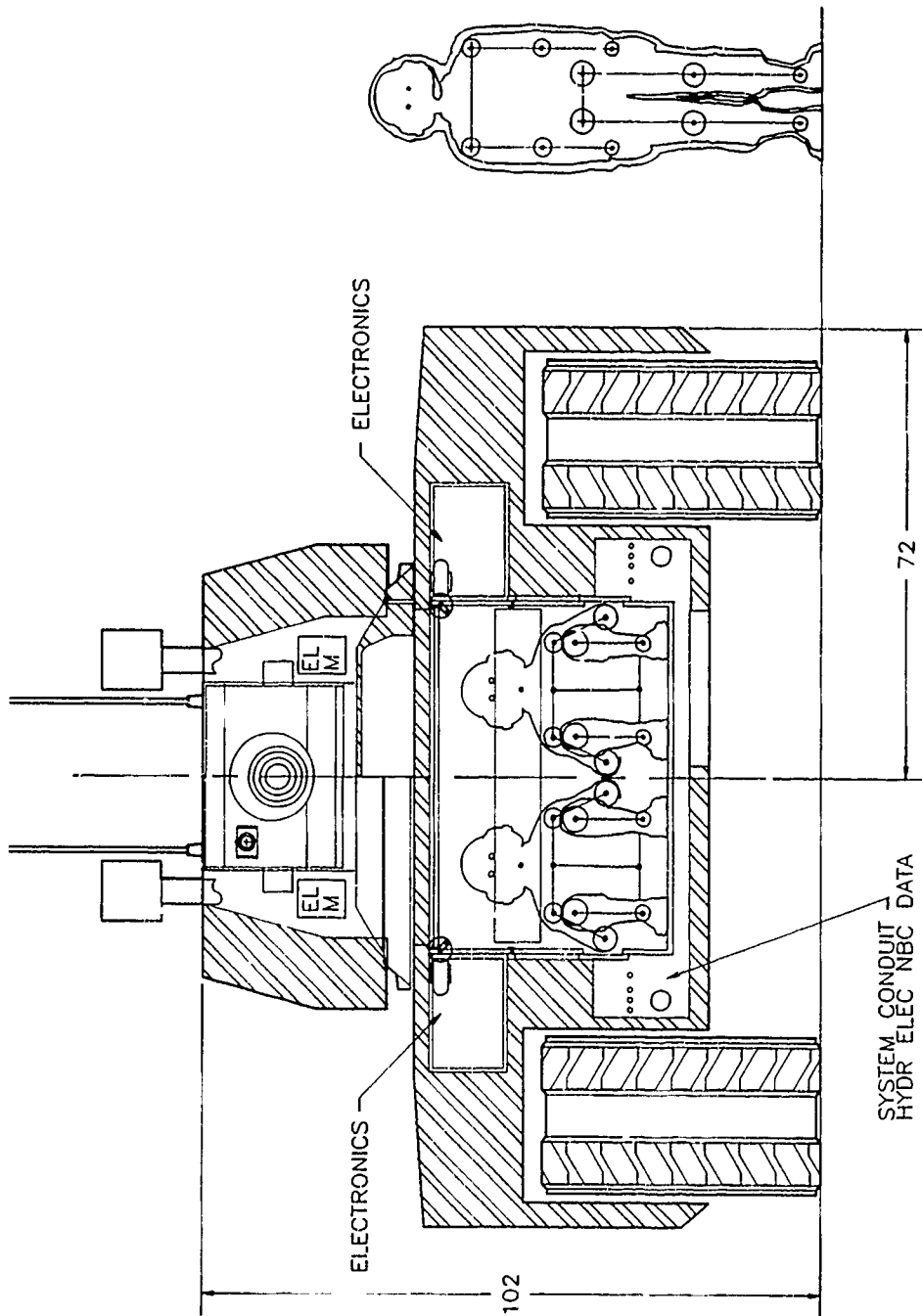
72

102

SYSTEM CONDUIT
HYDR ELEC NBC DATA

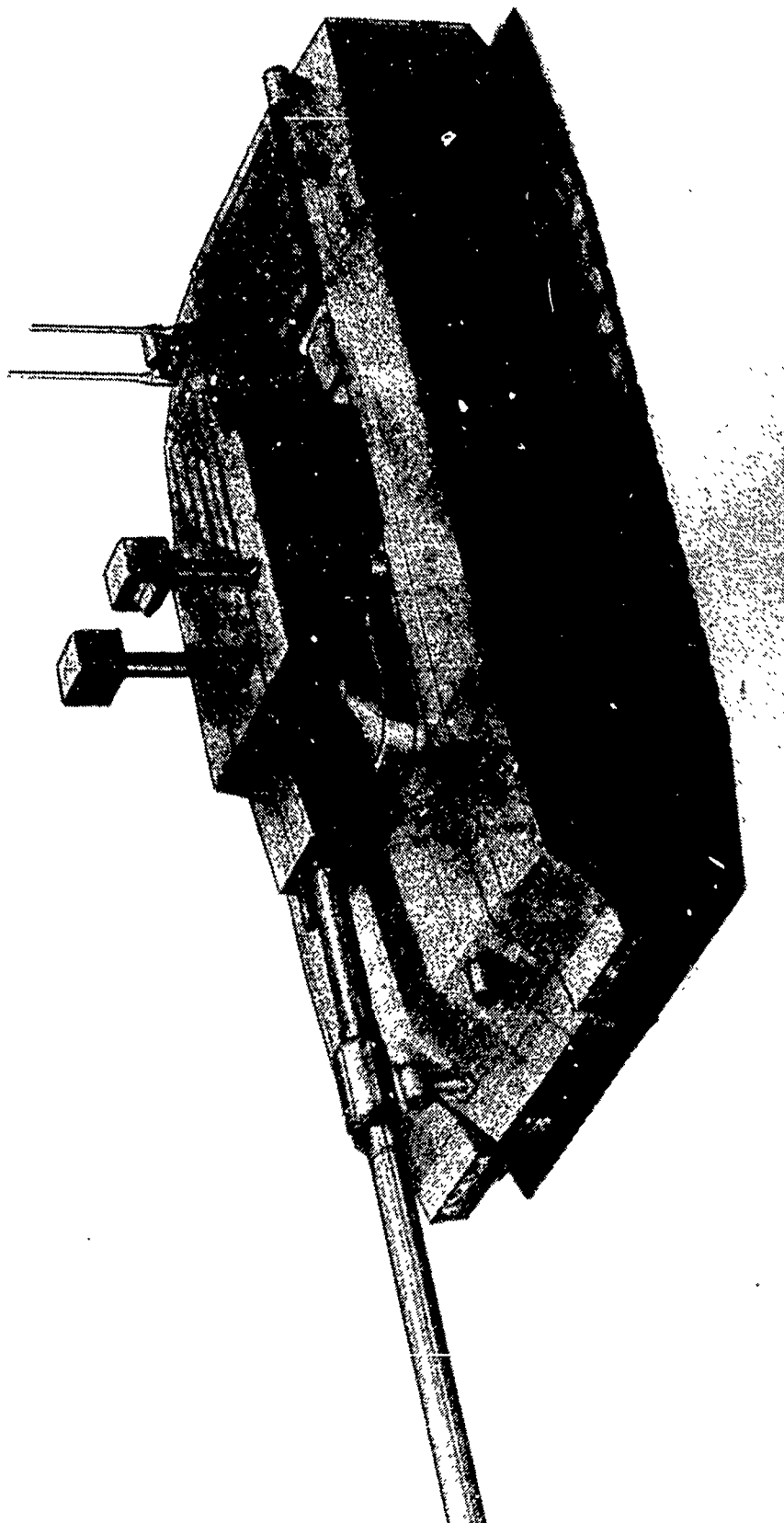Fig. 32—Two-man remote turret design: front view

Fig. 33—Perspective rendering of two-man remote turret design

arm positions. Spall covers with articulations are behind each crew member, ready to be pulled overhead to reduce top attack vulnerability. The hatches mate together in the center without a partition, so that each member can see out the other's visor. Finally, each of the hatches has both electric and manual drives for opening the armor and visor sections. These are shown in the side view of Fig. 30.

The NBC airflow paths are kept separate from the crewspace and from fresh air paths to the extent possible. Referring to Fig. 34, contaminated air comes in from the opening behind the left crewman's hatch and is routed by a 3-in. pipe to the NBC kit aft of the lower glacis. The NBC system outputs clean, conditioned air to the crewspace at the crewmen's feet, and then routes it to the electronics bays. Contaminated air is passed to a pipe that runs along the chassis to the rear of the vehicle.

The overall vehicle dimensions are considerably smaller than those of the M1-A1, as shown in the overlay in Fig. 34. Chassis length is reduced from 312 to 271 in., resulting in use of six instead of seven roadwheels. Turret height is similar, 106 to 102 in., but the two-man MBT has a turret cross section some 50 percent smaller than the M1-A1 from the front, and 40 percent smaller from the side.

Because most of the armor protection is in the hull frontal glacis (some 10 tons), the center of gravity of the vehicle is fairly far forward, between the second and third roadwheels. The overall weight of the vehicle is estimated to be 55.4 tons. The armor configuration results in good top attack protection for the crew when the gun is oriented in the forward direction, and at the same time results in a low turret frontal cross-sectional area. Most of the armor is composite type with moderate space efficiency, but the limited thickness on the sides of the crew require this "interior skirt" armor to be a high-density material such as tungsten or depleted uranium. We assume that the highly space efficient armor would have a low mass efficiency.

The mobility of the two-man remote turret design should be fairly good. At 55.4 tons and with the 1500-hp AIPS unit, it will have a power-to-weight ratio of 27.1 hp/ton. Ground pressure with the 25 in. wide tracks will be approximately 13 psi. The length-to-width ratio of the tracks will be very close to the ideal 1.5:1, resulting in good steering response. Because the forward slope and height are similar to that of the M1-A1, it should be easily able to climb a one-meter obstacle. The vehicle will carry some 330 gallons of fuel, corresponding to 1.3 battle-days.

Fire control should also be effective. Electric turret motors should give rapid turret traversing along with accurate low-speed target tracking. Elevation/depression is designed to be +20/–10 deg, with an additional +6/–6 deg from suspension kneeling (when facing forward). Crew vision angles in the open hatch mode cover roughly 270 deg total.

Secondary armament consists of a 7.62-mm coax in the turret with 10,000 rounds of ammunition. Optionally, the vehicle may have a 7.62-mm machine gun on one of the sensor masts, under the sensor pod. This gun would have a mounting concentric to the mast post with vibration isolation. A 3400-round ammunition box would be attached. The optional mast-mounted gun would allow the crew to engage soft targets away from the direction of the main gun. An interlock would be needed to assure the other mast is not hit.

Repair should be similar to that of an M1-A1; both have excellent engine access at the rear of the vehicle. Loading of the main gun rounds cannot be done by pallet because of the
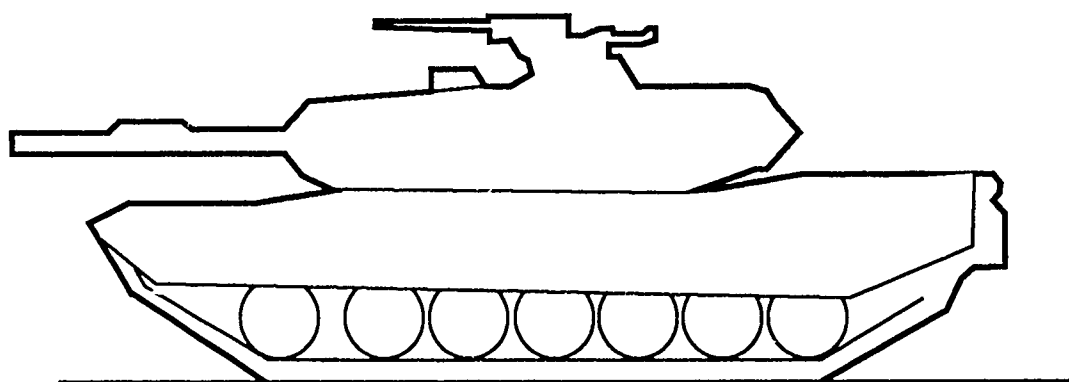
M1-A1
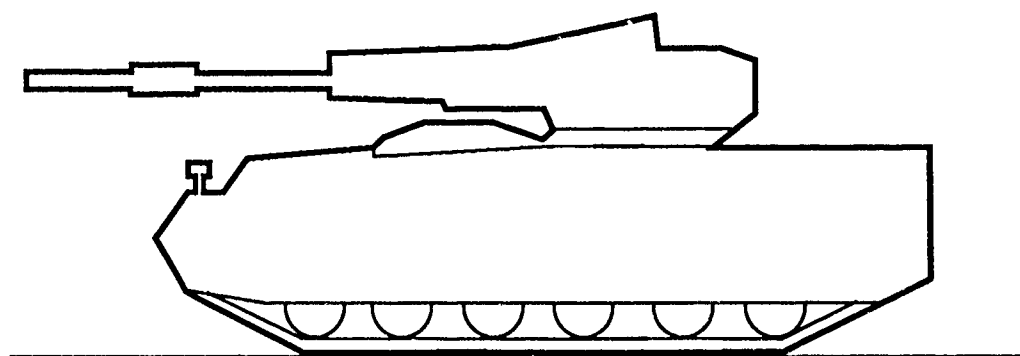
Two-man MBT

Fig. 34—Comparison of M1-A1 and two-man MBT

turret ring intrusion. Round cannisters are loaded individually into the rear portion of the turret ring, entering the outer conveyer system. This would be a slight improvement over the M1-A1, which is loaded through the loader's hatch. Depending on the mix of one-piece and two-piece rounds, between 35 and 70 rounds can be carried.

Three-Man Remote Turret Concept

We explored two designs with three men in the hull and a remote gun. The first is a three-abreast design, in which three crew members sit side-by-side in the crew compartment. This side-by-side design has the advantage of maintaining the overall dimensions of the two-man design, but results in extremely cramped and poorly protected crew members. Allowing 28 in. of shoulder area for each crew member results in complete removal of the interior skirt armor, the main side protection for the crew. Even reduction to 24 in. shoulder-to-shoulder and use of extreme high-density armors do not allow sufficient frontal arc protection. Widening of the tracks and outer side skirts is not possible. The two-man vehicle width is already that of the M1-A1, which is set to be the maximum for clearing tunnels during train transport in most European theaters.

Figures 35–37 show an alternative three-man remote turret design, in which the crew members are staggered, two forward and one back (the opposite—one up and two back—would be a less efficient use of frontal armor). As shown in Fig. 35, the vehicle is stretched some 32 in. longitudinally to accommodate the staggered crew. The crew compartment width is, however, substantially less than that with the three abreast design, because the rear crew member's legs fit between the two front seats. This reduced crew station width allows placement of sufficient high-density interior skirt armor.

The three-man complement significantly changes the crew activities. The rear crew member has reduced functionality compared with the front two, as he has no hatch (precluded by the gun overhang) and enough room only for a flat panel display. He does have some room to recline. The lengthened crew compartment also results in space for personal equipment and rations behind the two forward crew members.

There are some questions about who does what in this design. The center rear crewman might be the commander, as he has the central position overlooking the other crew members. However, this position has the least room for controls and displays, and its out-the-hatch and hard optics views are occluded from the side by the other two hatches. The center back might instead be the gunner's position; it should not be the driver's because there is no room for foot pedals. If the gunner is in this position, he might be a good candidate for a head-mounted display, with the other two operators having CRTs and flat panel displays. One of the forward positions would then be the commander and the other the driver/radio/maintenance man.

Some habitability advantages accrue from the three-man design. In periods of low to moderate activity, the center crew member can sleep, allowing cycles of 16 hours on, 8 hours off. The spaces to the rear of the two forward crew members should allow the crew to switch positions without exiting the tank. These spaces can also have mini-toilets, electronics panels into the sponson areas, and food/drink dispensers. Swing-away doors may seal these areas during combat, so that spall will be minimized. The far forward hatch placement will
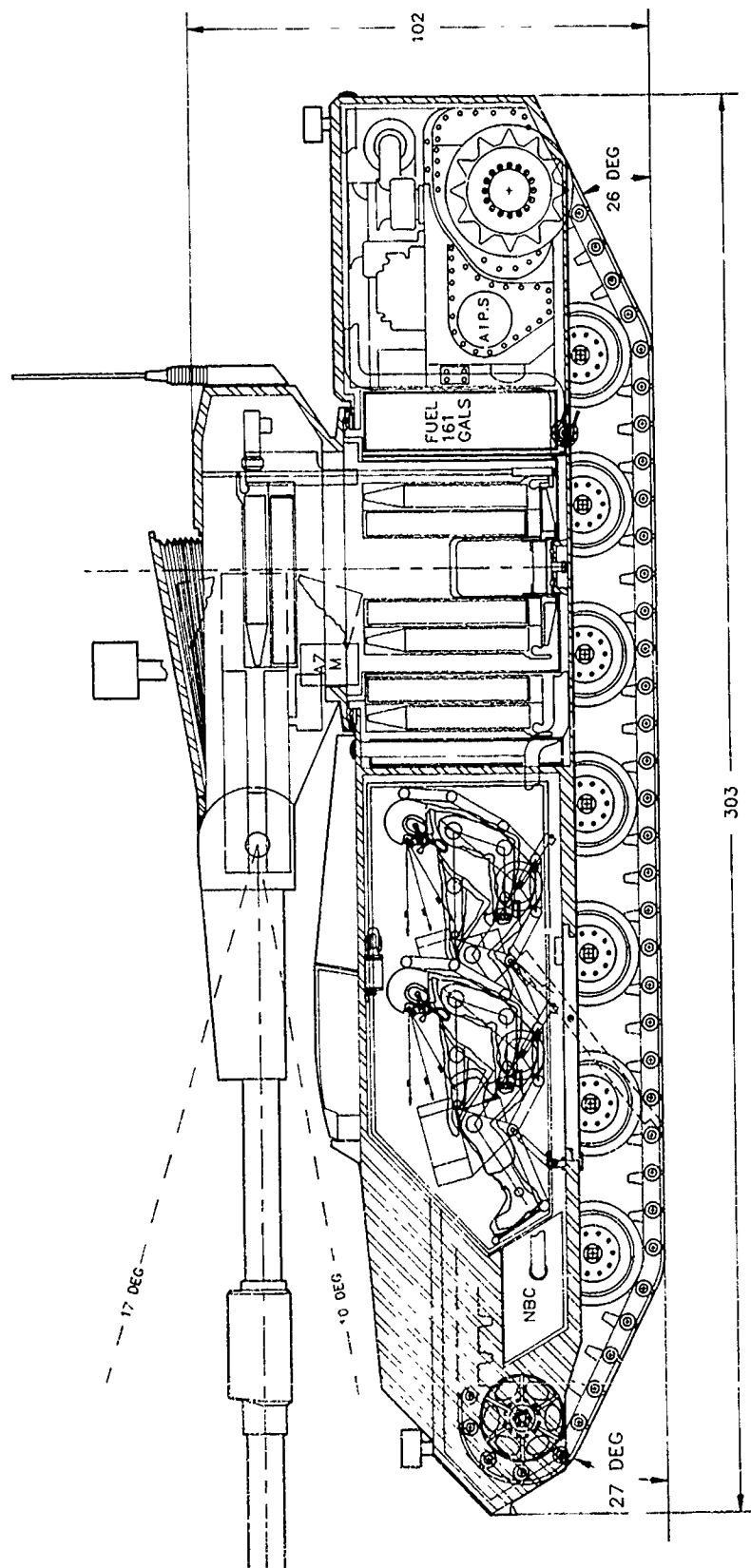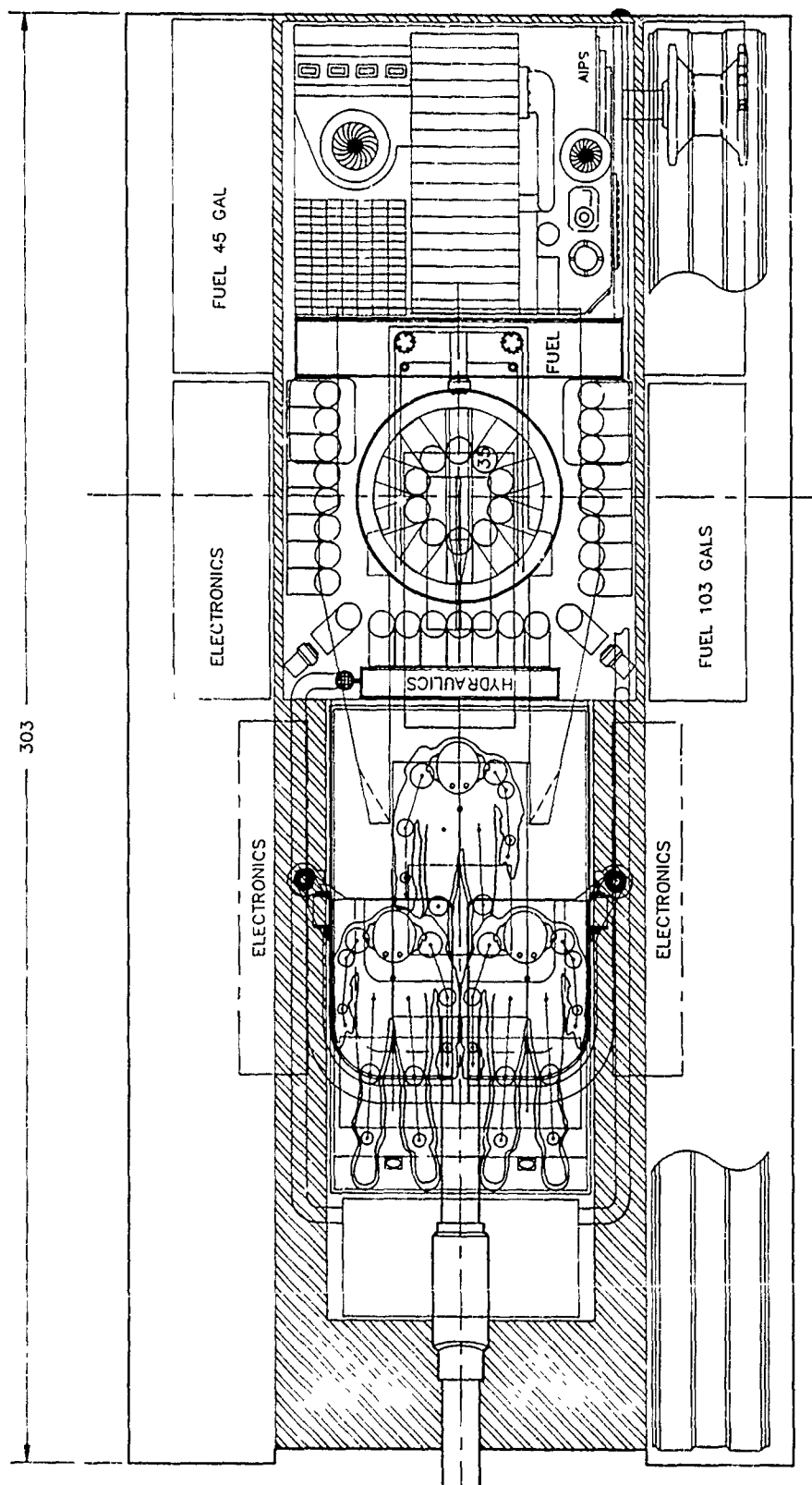
Fig. 35—Three-man remote turret design: side view

Fig. 36—Three-man remote turret design: top view

ELECTRONICS

ELECTRONICS

ELECTRONICS

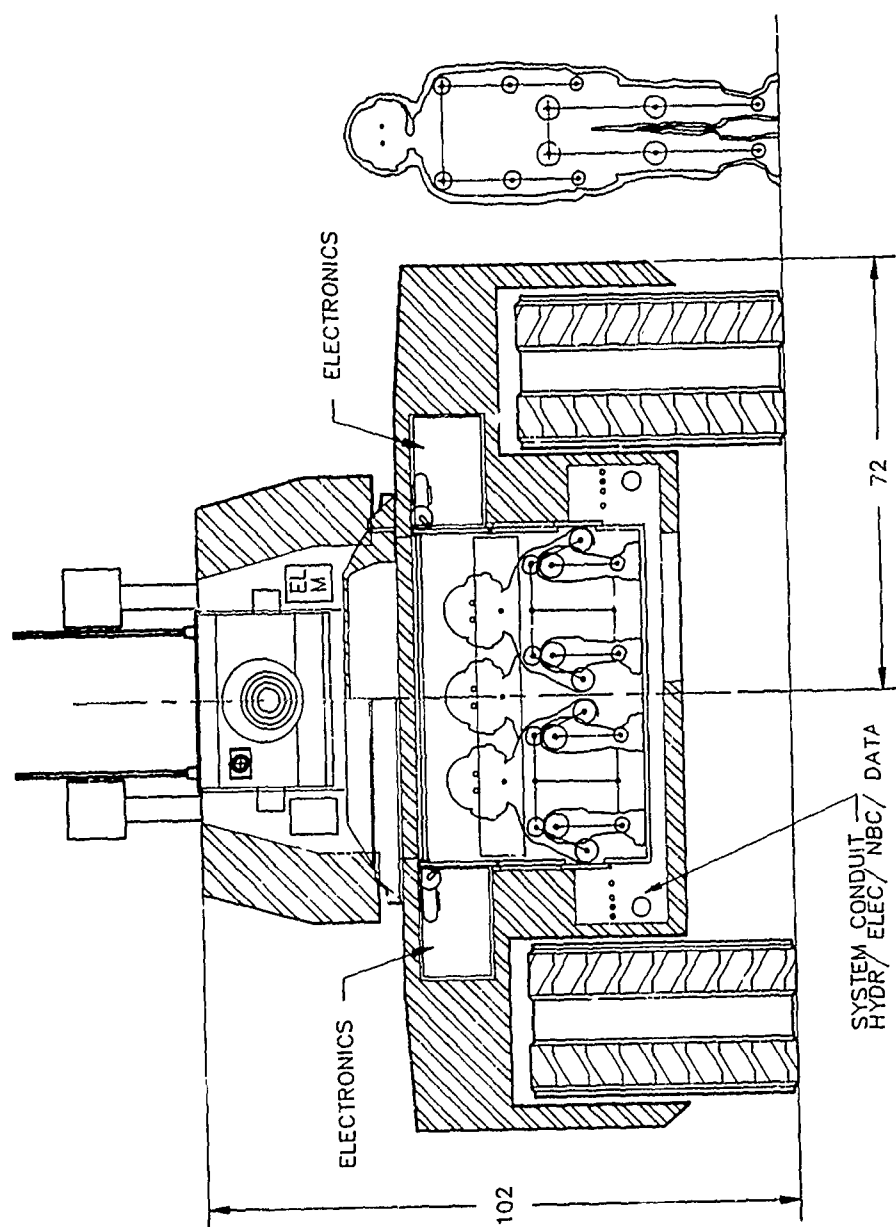102

72

SYSTEM CONDUIT
HYDR/ ELEC/ NBC/ DATA

Fig. 37—Three-man remote turret design: front view

facilitate ingress and egress, although the gun overhang will no longer provide as much top attack protection as in the two-man design.

The design adds some size and weight to the vehicle. The length is increased by 30 in. over the two-man design, although muzzle overhang is reduced by a similar amount. The length-to-width ratio changes from 1.5 to 1.7, but ground pressure is similar to that of the two-man version, due to longer track and addition of a roadwheel (from six to seven). The overall vehicle weight goes up by 5.5 tons to 61 tons, resulting in a power-to-weight ratio of 24.6 hp/ton. The vehicle should be air transportable by either the C-5 or the upcoming C-17.

Three-Man, Two-in-Turret

In all the the crew-in-hull designs described, there is no provision for unobstructed 360-deg out-the-hatch viewing by the commander, which some analysts feel is essential.[4] A design that makes this possible is shown in Figs. 38–40. It is a more conventional crew-in-turret design, with the commander and gunner in the turret and the driver in the chassis. The advantages of this approach are (1) all-around commander/gunner viewing, (2) alignment of the gunner with the gun direction, reducing orientation problems, and (3) access to the breech in case of autoloader jams.

The crew-in-turret version is essentially the Soviet design, except with compartmentalized ammunition, full-size crew members, more armor protection, and much more extensive electronics. In many ways, the design is closest to that of the upcoming French AMX LeClerc and Japanese TK-X tanks. The disadvantages with the manned turret are that frontal arc protection is extremely heavy, top attack protection is limited, defilade cross-section is much larger than with a remote gun, and a carousel loader cannot be employed. Although Soviet vehicles employ horizontal carousel loaders, we felt that this would be nearly impossible given large two-piece ammunition and the requirement that ammunition and crew be compartmented. We explored two basic designs: (1) a divided ammunition space, with a portion of the rounds in joined form in the turret bustle and a portion in two-piece separated form in a hull compartment behind the crew, and (2) a unity space with all the rounds already joined in the turret bustle. We chose the first design for our configuration, because the second would require an excessively wide or high turret bustle.

The turret crew members again have sensor masts for button-down operation in this design, but they have the option of out-the-hatch all-around direct view. Unfortunately, even this mode has problems, since the commander must get high enough to clear the turret for 360-deg viewing, by which time he should be exposed almost to the waist (halfway to heaven, as Simpkin puts it[5]). Both crew members together may be able to achieve 360-deg viewing with only their heads above the turret roof.

Some special access and coordination means are present with this design. The driver has an open pathway to the turret area (at least when the gun is centered), and so can enter and exit through the top hatches. The driver also has his own small hatch along with a floor hatch. In an emergency, the commander and gunner can abandon the tank by moving

---

[4]Jacques Lenaerts, "Design Criteria for AIFV Turrets," *Military Technology*, No. 3, 1988, pp. 16–24.

[5]R. E. Simpkin, *Human Factors in Mechanized Warfare*, Brassey's, New York, 1984.
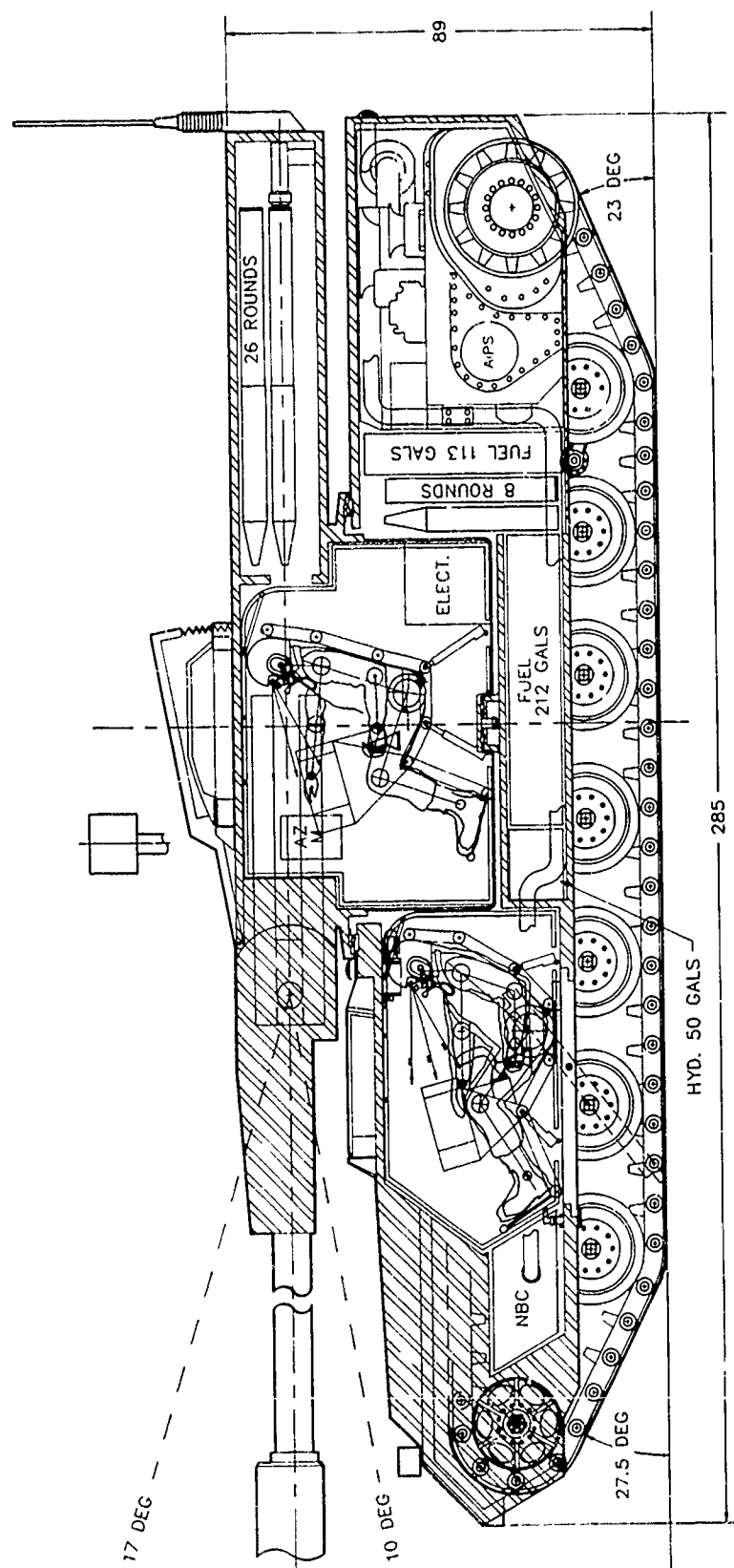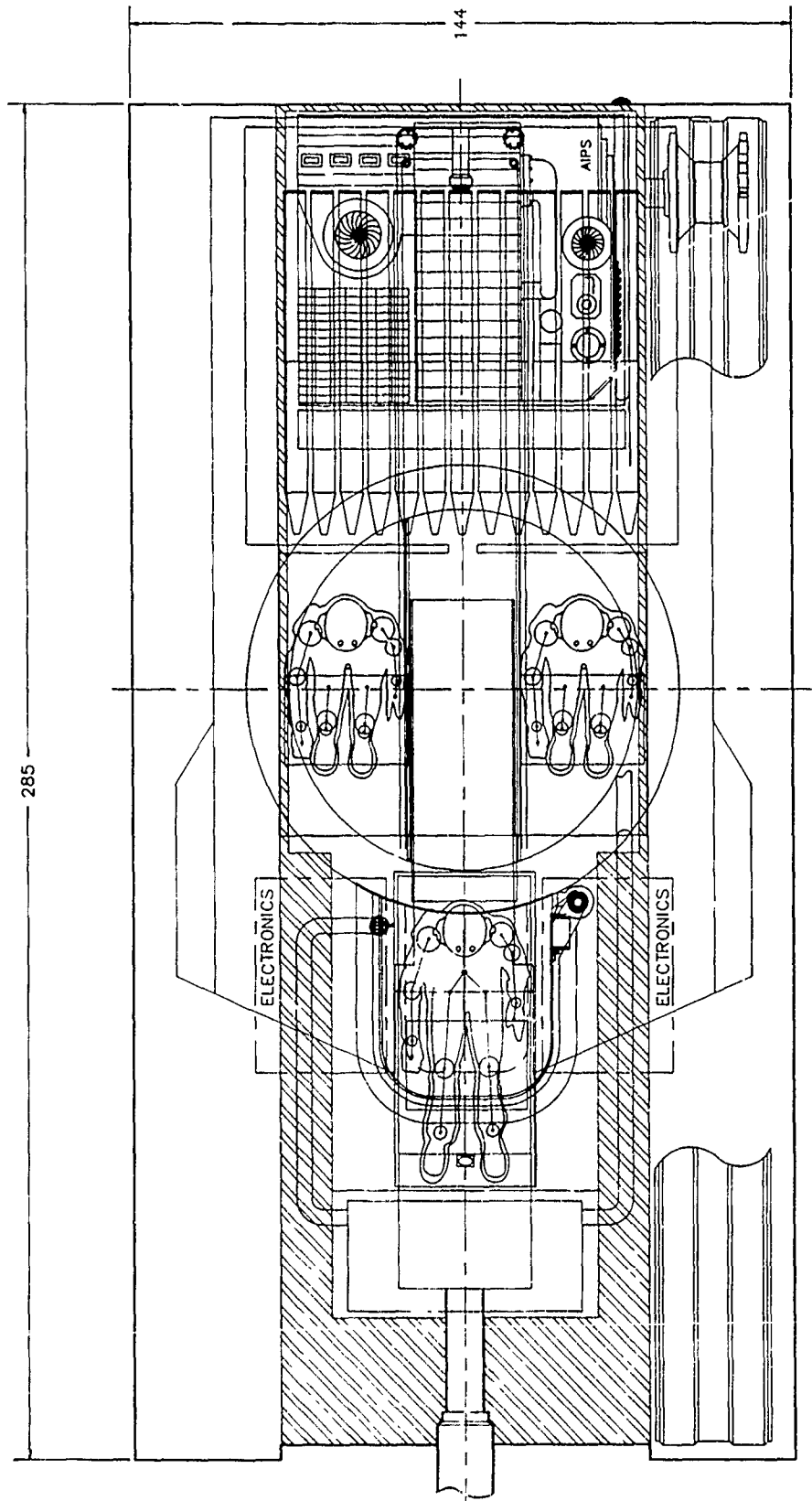
Fig. 38—Three-man, two-in-turret design: side view

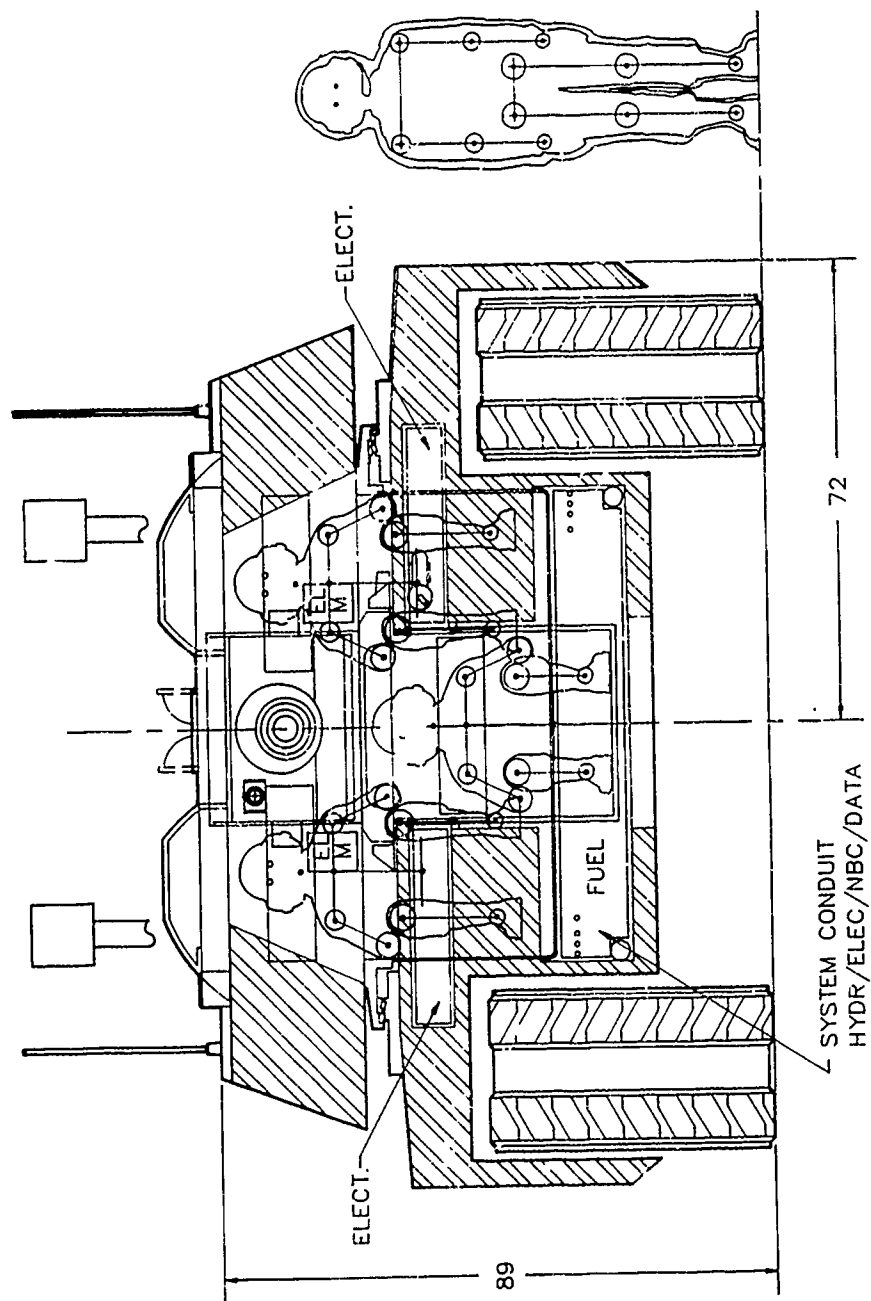Fig. 39—Three-man, two-in-turret design: top view

Fig. 40—Three-man, two-in-turret design: front view

through the driver's compartment and exiting through the floor hatch. The two crew members in the turret are on different sides of the gun, but can coordinate through the space between them. They have to be protected from gun recoil by a heavy mesh, but they should be able to communicate through this. There is also a special ammunition loading hatch at the rear of the bustle.

Depression of the gun presents some special problems, both in this and the other designs. Figure 41 shows a hinged cover on top of the turret that raises up to protect the gun breech. When the gun is raised, the hinged cover drops down, reducing the turret silhouette. However, it introduces a structural weakening in the turret. German designers originally favored such a hinged cover for their future tank, but changed instead to a fixed "blister."

The driver in the hull takes up less room than a two-man crew, and so high mass efficiency armor can be used for side protection instead of the high-density space efficient armor used in the two-man design. Also, the forward area will have room for a larger NBC unit, needed for the larger crew space.

The manned turret MBT would be quite massive, estimated at 74.2 tons and requiring seven roadwheels. The Soviets make a much smaller tank by having the gunner sitting on the ammunition and almost under the gun, jamming the driver in the forward hull, using somewhat thinner armor protection, employing small crew members, and firing much shorter rounds. These options are not open to us.

Three-Man, One-Behind-Turret

A novel design allowing all-around commander viewing is shown in Figs. 41–43. Here a two-man crew occupies the forward crewspace in the chassis, and the commander sits in an armored enclosure directly behind the gun. This design uses the existing massive gun armor to protect the commander against forward threats. It allows him to survey the battlefield from the top of the tank, and it maintains his orientation with the gun. The problems, however, are again numerous. Extensive communication links, NBC connections, and duplicated displays are needed for the two crew compartments. This is especially important when different crew members are tracking different targets. The commander has no recline position and probably will be quite cramped. He suffers recoil shock from the weapon. The sensor masts for the other crew members occlude part of his view.

There are also many tradeoffs with respect to protection. There is good flank protection for the gun, but when the gun is rotated, the commander is exposed and only thinly armored. Top attack protection is similarly low for this crew member.

The man-behind-turret design should again be quite massive. We estimate the total weight to be 74.5 tons, resulting in a 34 percent increase in ground pressure compared with the two-man version, and a corresponding decrease in hp/weight ratio, to 20:1. A major problem will be the increased cross-section of the turret. It is 29 in. wider and 8 in. taller than the two-man version.

SUMMARY AND CONCLUSIONS

Each of the four designs has its own merits, and each should respond differently to new technological developments. Mobility, protection, signature, and cost all favor the two-man
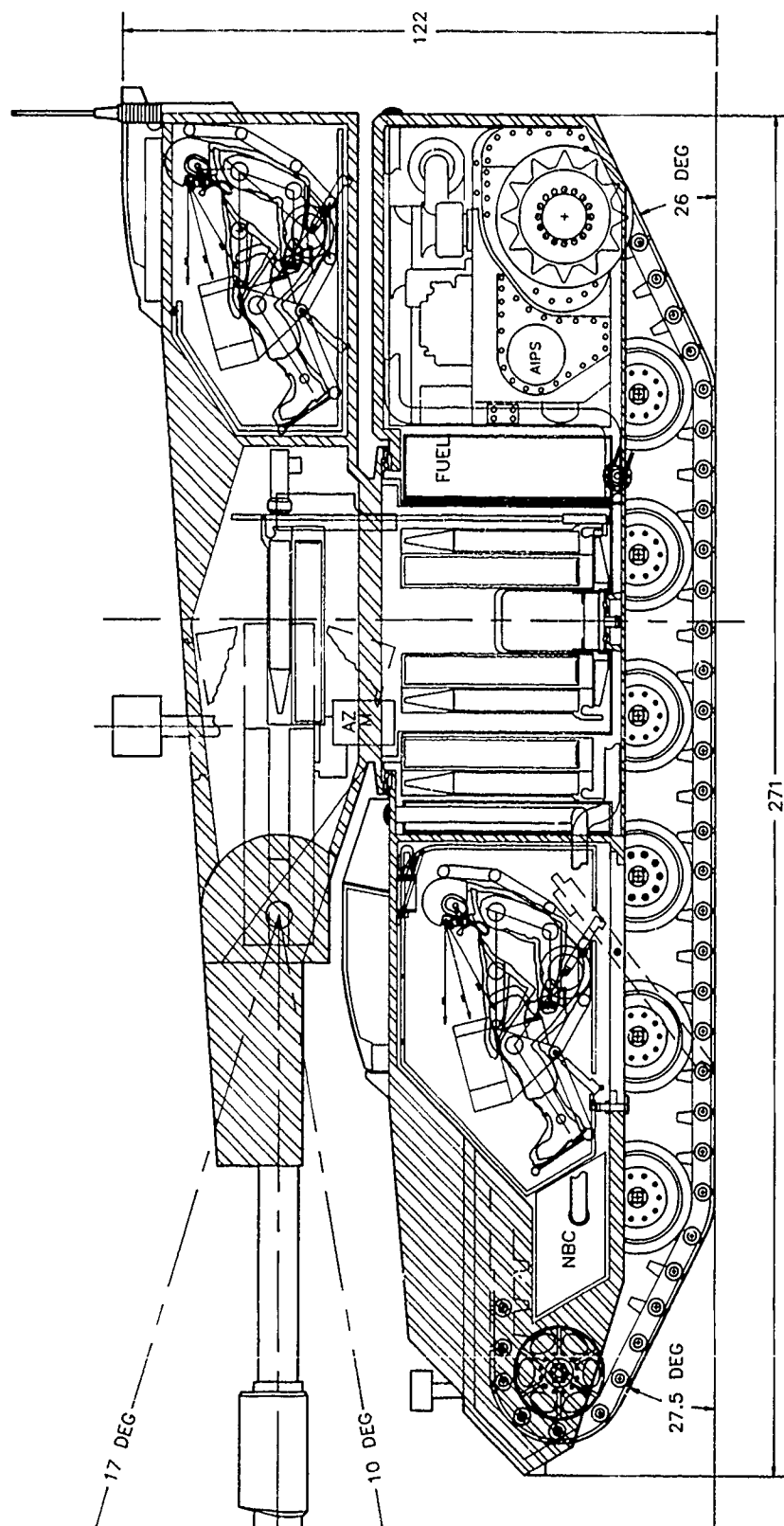
Fig. 41—Three-man, one-behind-turret design: side view
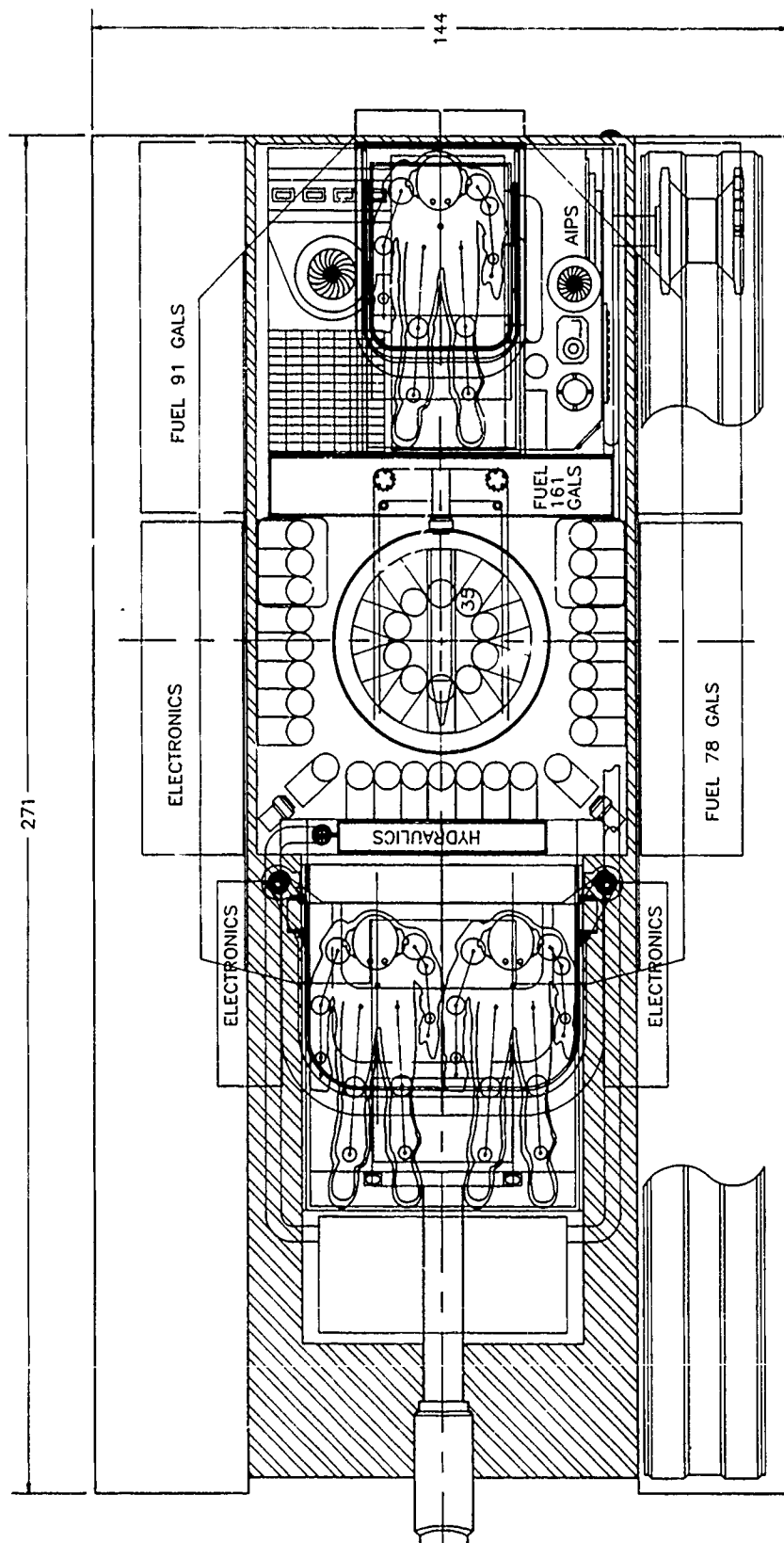
Fig. 42—Three-man, one-behind-turret design: top view
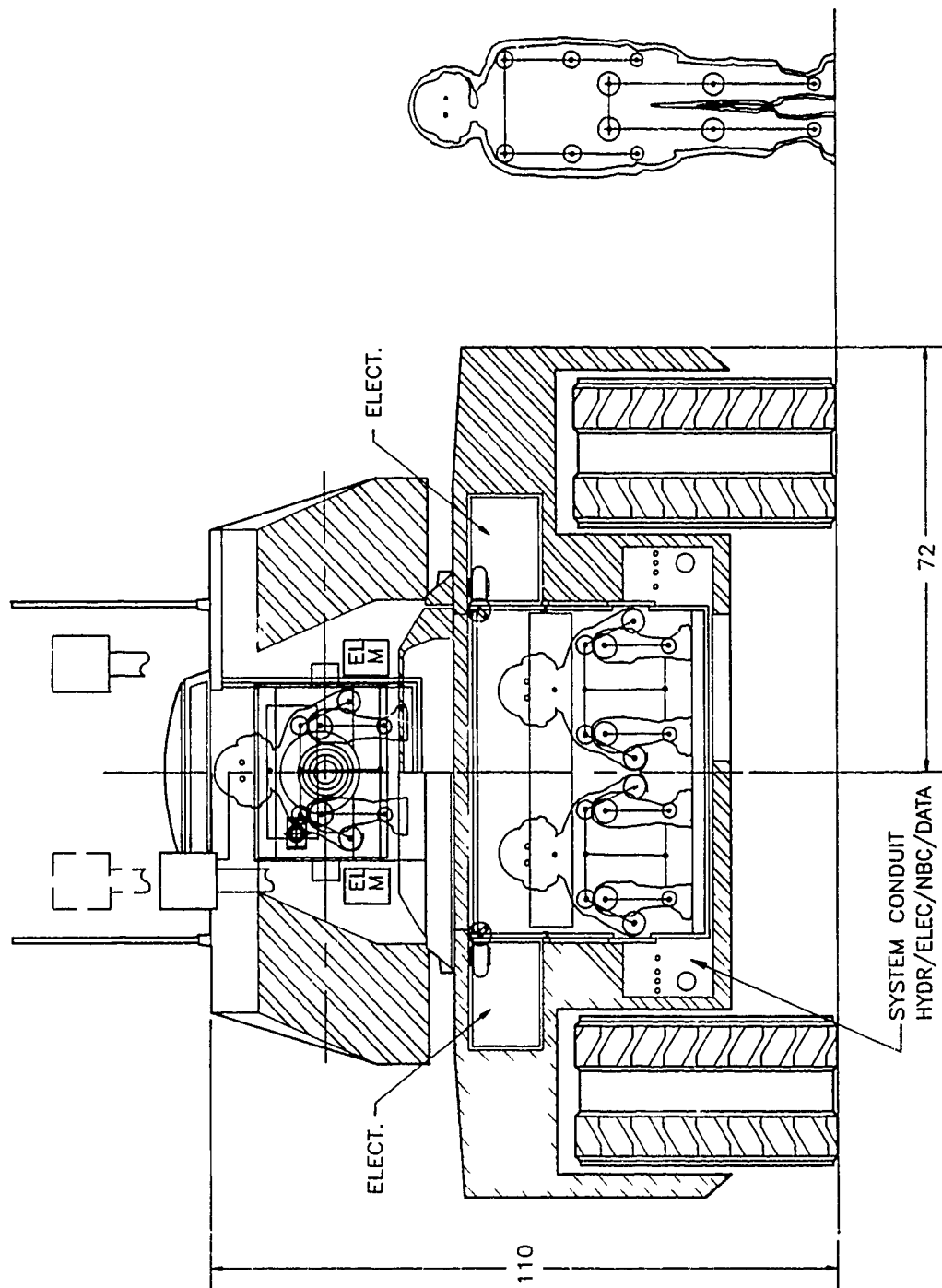
Fig. 43—Three-man, one-behind-turret design: front view

remote turret design. Improvements in sensors, displays, and automation should be especially important to this configuration. Overall battlefield viewing capabilities and gunner orientation favor the crew-in-turret and one-behind-turret three-man designs. These designs would benefit most from more efficient armors and more powerful propulsion systems. Long-term operations and close crew interactions favor the three-in-hull design, which would be aided by breakthroughs in sensor and display technologies along with new armors.

A breakdown of component weights for each of the four designs is given in Table 8. The main differences are in armor and suspension masses, with almost a 20-ton difference separating the extremes.

Table 8

COMPONENT WEIGHTS FOR MBT DESIGNS
(In kg)

Component	Two-in-Hull	Three-in-Hull	Two-in-Turret, One-in-Hull	One-Behind-Turret, Two-in-Hull
Autoloader+35 rounds	2600	2600	2600	2600
Gun assembly	2800	2800	2800	2800
NBC	280	320	350	350
Hydraulics	510	510	510	510
Electronics	900	900	900	900
Turret components	1500	1500	2000	2000
Fuel	1200	1200	1500	1200
AIPS	5000	5000	5000	5000
Armor	25200	28800	37800	38300
Crew stations	800	1200	1200	1200
Suspension	9550	10500	12800	12800
Total	50340	55330	67460	67700
(U.S. tons)	(55.4)	(60.9)	(74.2)	(74.5)

V. LIGHT ARMORED VEHICLE DESIGNS

INTRODUCTION

Exploring designs for light armored vehicles was a much simpler process than the full MBT design effort described earlier. We simply took existing vehicles and modified them to mount hypervelocity missile (HVM) launchers and advanced crew stations. The intent was to quickly develop a long-range antiarmor capability using platforms such as the Bradley fighting vehicle and the Marine Corps light armored vehicle (LAV).

No major modifications were planned for the drive trains, suspensions, or armor of the Bradley and LAV platforms because the mission would not be one of spearheading an attack, but rather long-distance antiarmor operations or defensive actions. The main modifications involved adding hypervelocity missiles, updating the sensors and electronics, and reworking the crew compartments. As in our MBT designs, we explored two-man and three-man versions for each concept.

HVM BRADLEY FIGHTING VEHICLE

Our design for the Bradley called for replacing the 25-mm cannon and TOW-2 missile pod with a hypervelocity missile module. We removed the gun turret, filled the entire rear of the vehicle with three-meter HVMs in two-round clips, added a lift/rotate/control mechanism for the missiles, and modified the crew compartment to place two to three operators in tandem. The propulsion, suspension, and armor protection packages were not changed from the current Bradley, although some fuel cells were moved to the floor area.

Two-Man Design

This configuration is shown in Figs. 44 through 46. Some 28 missiles are stored two to a pod in the ammunition compartment, along with (optionally) another four in the launch device. The missiles are raised four at a time, rotated toward the target, launched, and controlled by a laser link. According to LTV, developer of a hypervelocity missile system, as many as three at a time can be launched and controlled, provided they are within a specified angular envelope. The design shows a two-man crew in line on the left side of the vehicle (engine and drive train occupy most of the right side). The displays and controls provided to the crew are essentially the same as those specified for the MBT. The main difference is that each crew member has his own flat panel map display. The display and control panel spans the full width of the crew compartment. The sensor complement will also be similar to that of the MBT, except that only one telescopic mast will be fitted. The mast package will contain the mini-FLIR rather than the CITV version. The sensor package mounted on the HVM li⌐ ⌐chanism will constitute the main FLIR. Unfortunately, there are still some questions ⌐ he size and performance of the main FLIR. It is expected to be quite powerful, in order to acquire targets at the range of the hypervelocity missile. Electronics (signal
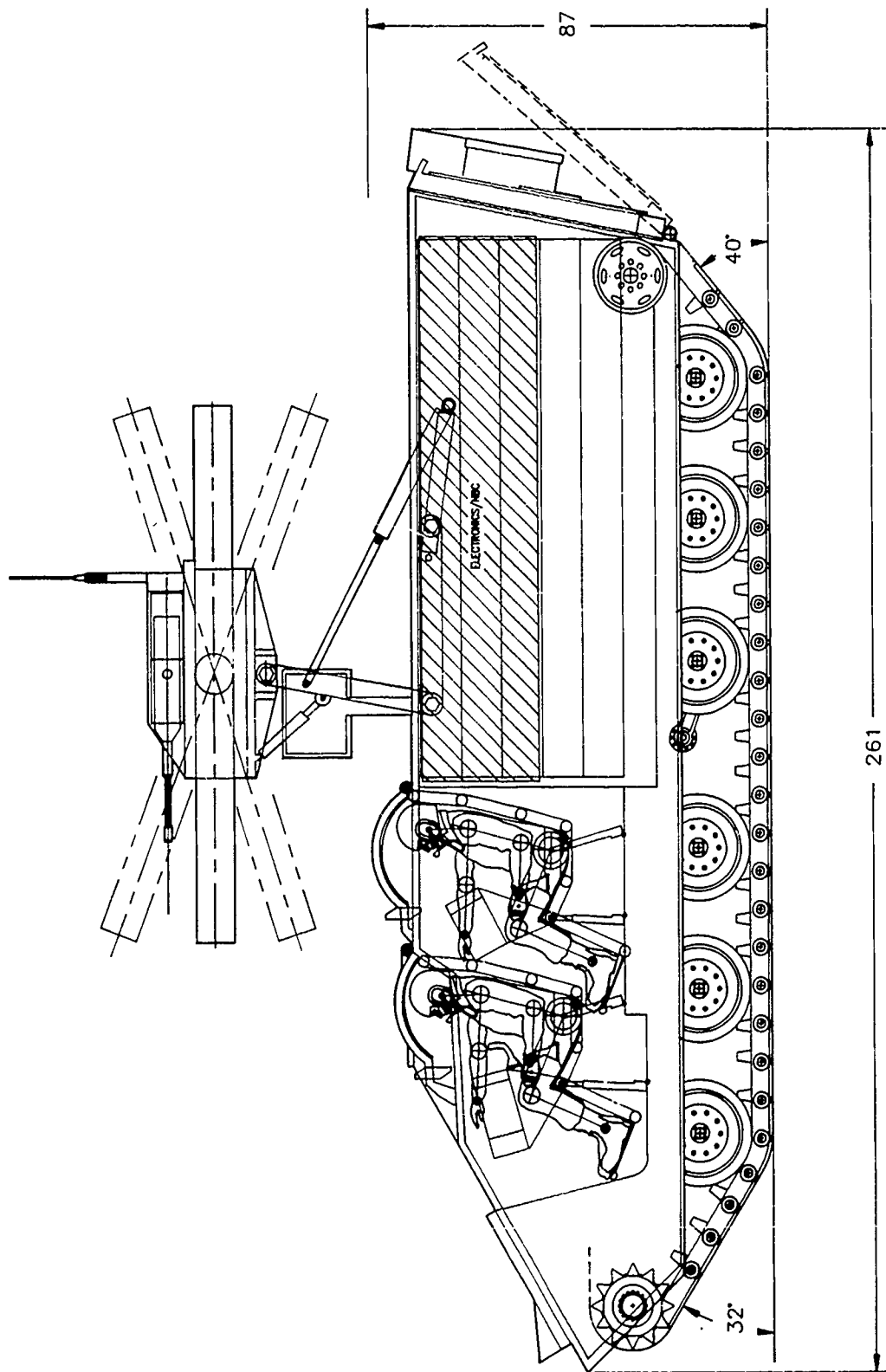
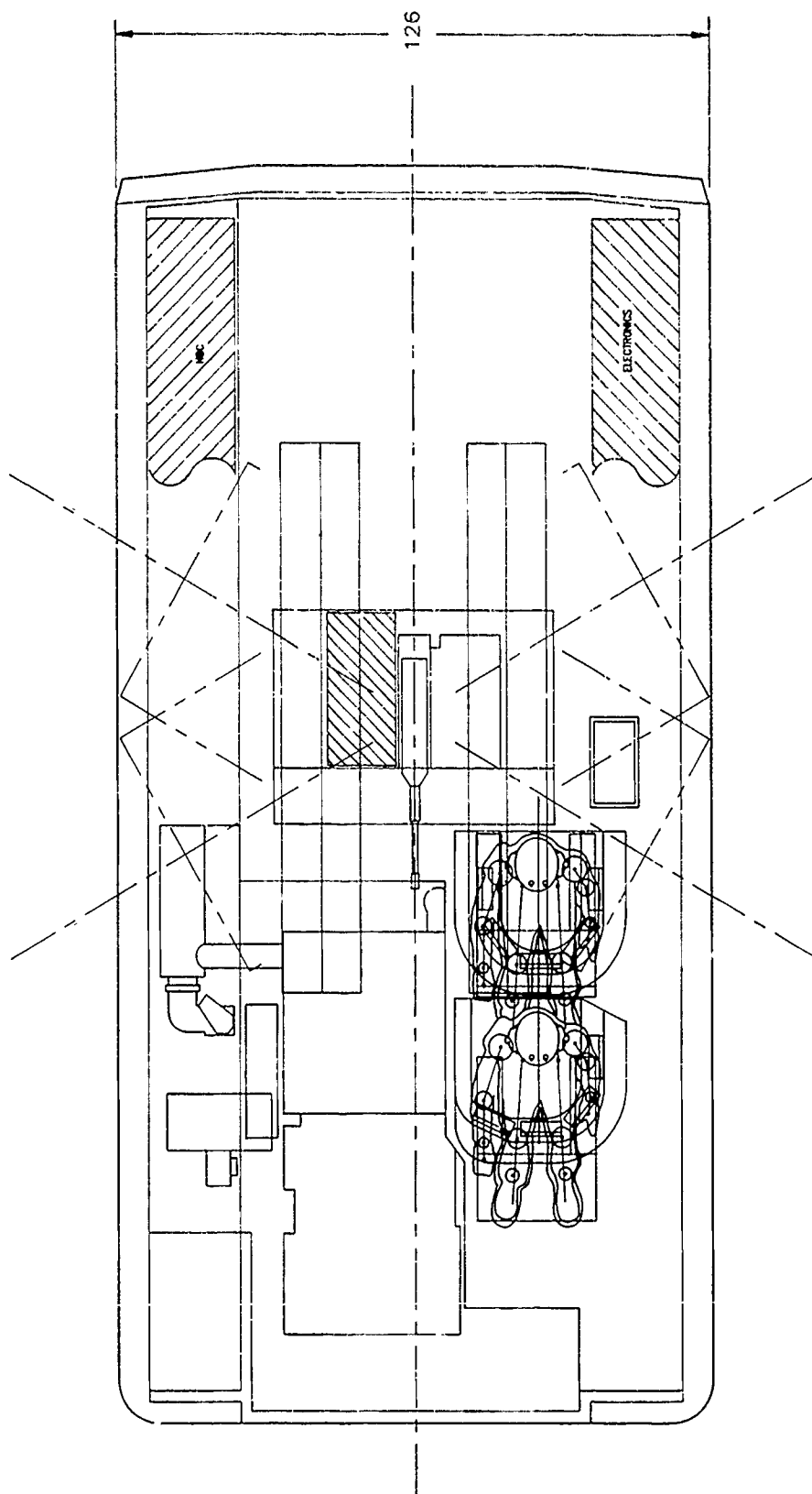Fig. 44—Two-man HVM Bradley: side view

109

Fig. 45—Two-man HVM Bradley: top view

Fig. 46—Two-man HVM Bradley: front and rear views

processors, main computer, network controllers, etc.) will be positioned over one sponson, whereas the NBC system will be over the other. These occupy roughly the same space as in the MBT, due to the similarity of functions.

We considered several options for elevating, orienting, and firing the missiles. Among these were a rotating turret mounted to the ammunition compartment floor, a scissors configuration mounted to the rear chassis roof, and the multilink hydraulic lever system shown in the figures. We found the 360-deg rotating turret required too much interior room, and the scissor system allowed only a 60-deg swing by its turntable. The multilink system shown gives full rotation, good rigidity and height control, and takes up very little room. When the launch device is down, the mast sensor can be set to any height. When the device is up, the mast sensor can take up an intermediate height position.

The missile transport mechanism is fairly straightforward. The missile pods are initially loaded through the rear door. The lift device drops down into the missile compartment and grabs two missile pods by rotating pairs of cams that catch the lower beveled edges of the pods. Pods in the middle of the compartment are transported to the sides when space is clear. After the second missile is fired from a pod, emptying the container, the pod is ejected by releasing the cams and letting the missile plume force it back. If this fails, a chain system runs the empty pod back.

Some special additions are needed for HVM firing. The exhaust plume from the missile is quite powerful, so doors must be fitted to protect the sensor packages, the other missiles in the lift mechanism, and the missiles in the chassis. Only the 7.62-mm coax gun is not fitted with protection. This gun has a protected 3400-round ammunition compartment next to it.

The division of responsibility between crew members is similar to that of the two-man MBT. The commander will be primarily searching for new targets, using either binoculars, mast-mounted electro-optical (EO) devices, or the mini-FLIR. He may also drive, radio other vehicles, or troubleshoot inoperative systems. The gunner will use the high-power FLIR mounted on the missile structure to identify, track, and fire at targets. He may also perform driving, communication, or troubleshooting functions.

The length and width of the HVM Bradley are identical to those of the current Bradley; the weight changes from 25 to 32.7 tons. The height (with HVM launch device down and 24 missiles) decreases 14 in., from 100 to 86 in. As with the MBT designs, we show 95th percentile male crew members in the figures.

Three-Man Design

A three-man design for the Bradley HVM vehicle is shown in Figs. 47 through 49. In this design, the commander sits in front of the lift mechanism, achieving an all-around view when the missile lift mechanism is down. The commander's station reduces the weapon load from 28 to 20 missiles, which results in some design compromises. For example, the commander is shoulder-to-shoulder with the missiles and has somewhat limited interaction with the other crew members. He has room for only the two CRTs and the communication panels, so that status information must be overlaid on the map or sensor displays. He is able to stand up and survey the battlefield unobstructed when the HVM module is down, but then he blocks the HVM sensor package. He can stand when the module is up, but his vision is re-
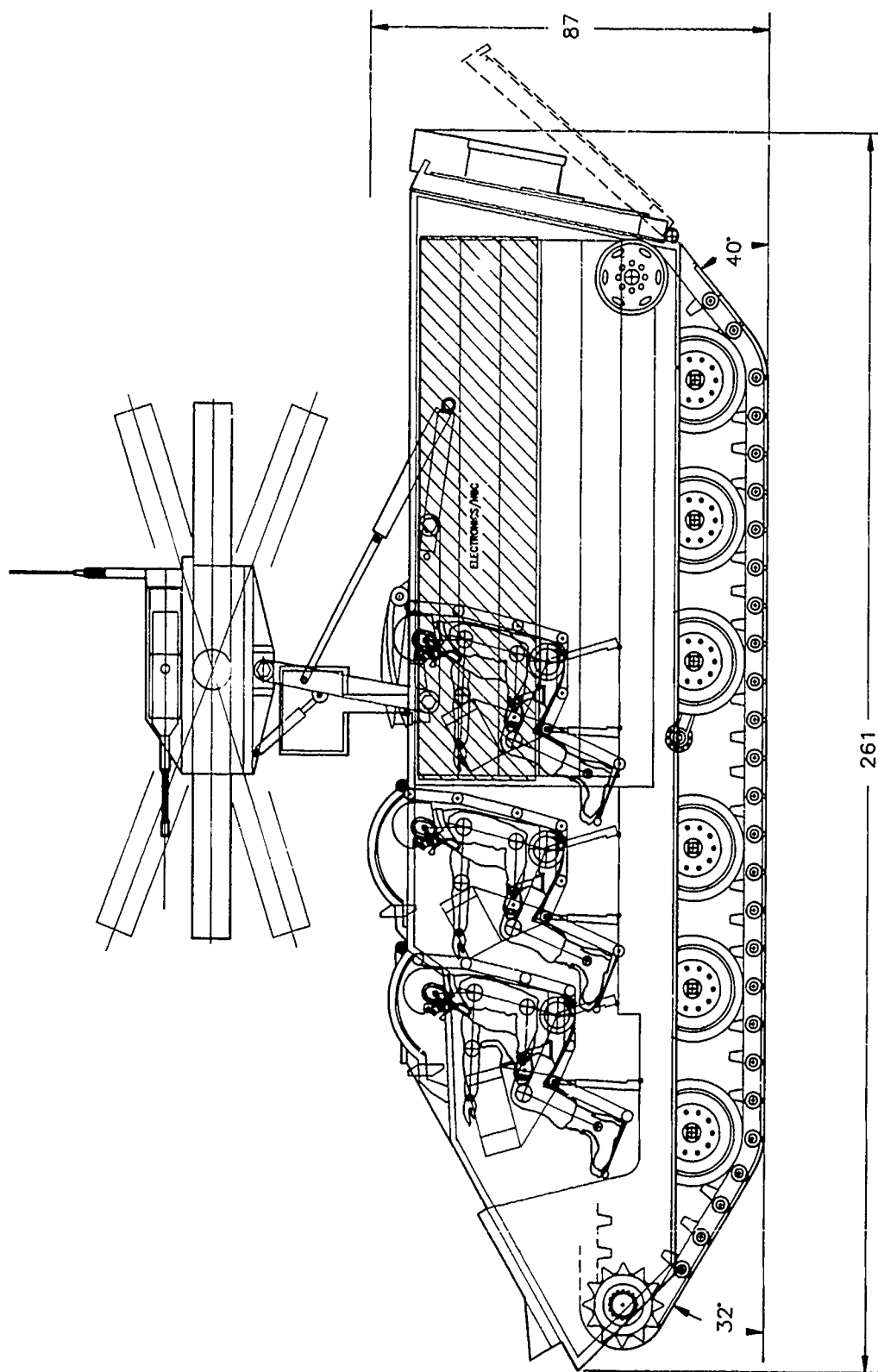
112

Fig. 47—Three-man HVM Bradley: side view
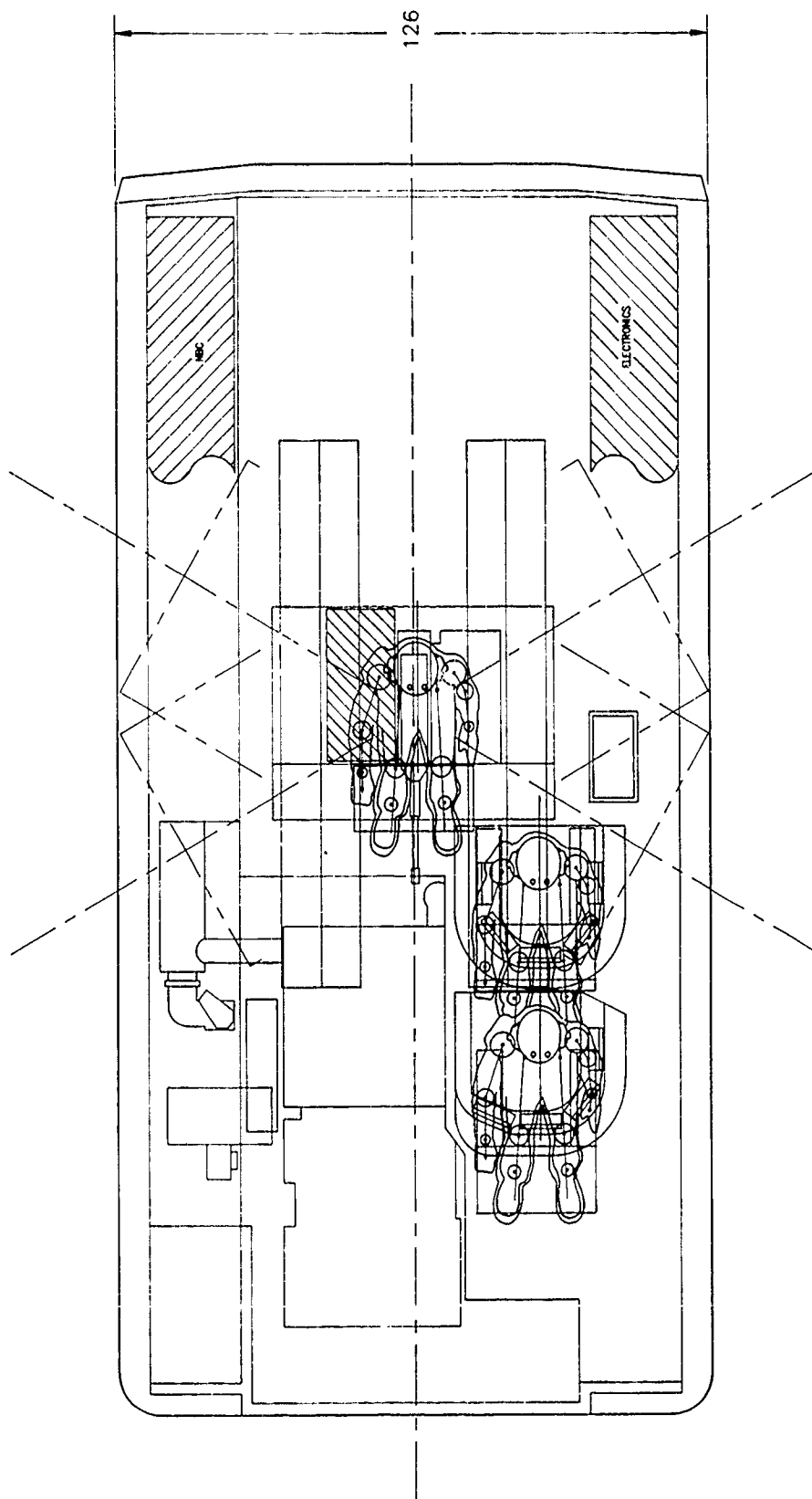
126

NBC

ELECTRONICS
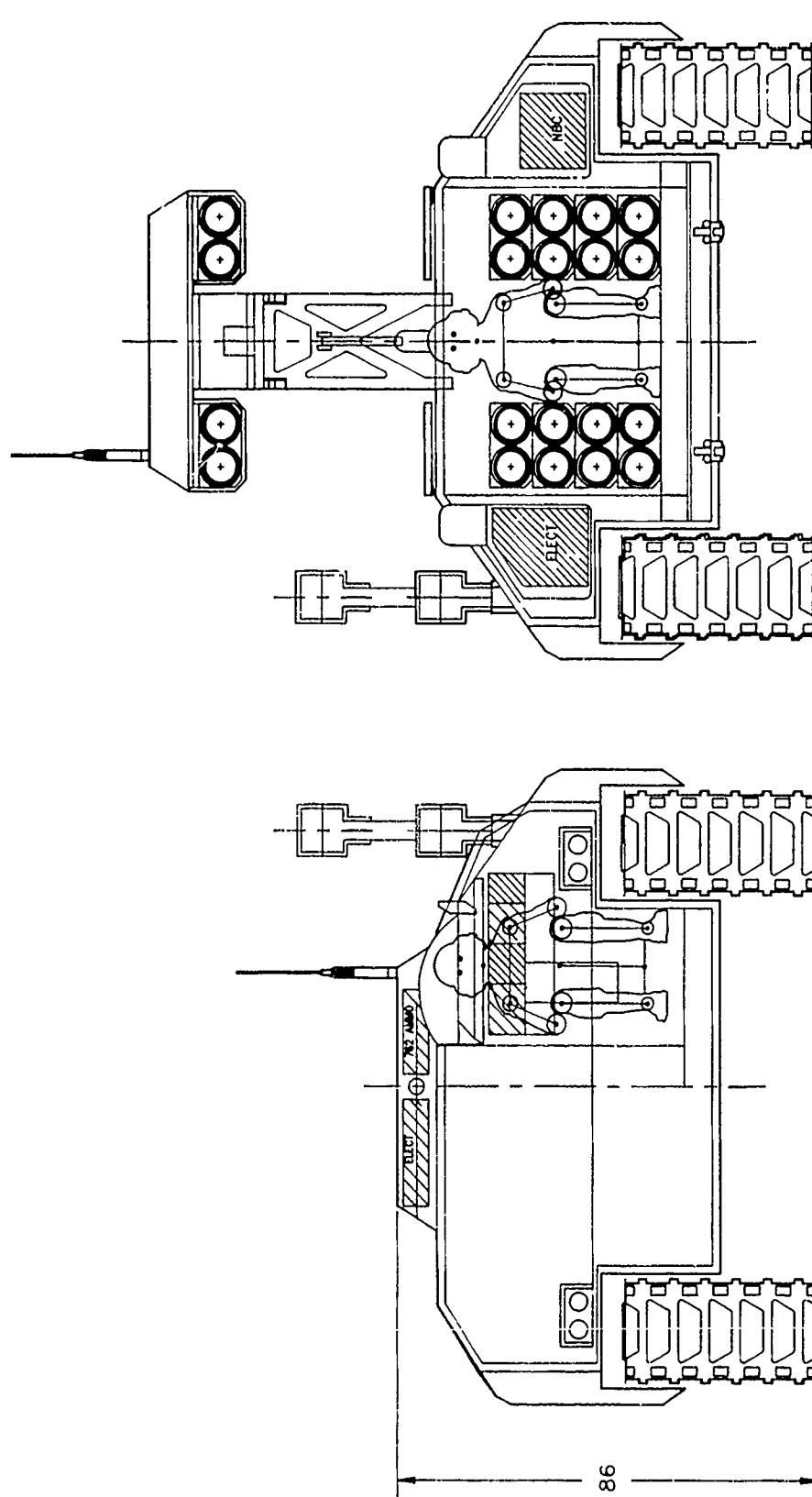
Fig. 48—Three-man HVM Bradley: top view

Fig. 49—Three-man HVM Bradley: front and rear views

duced by the supports and the telescopic mast sensor pod. The other characteristics of the three-man design—chassis, lift mechanism, sensors, etc.—are identical to those of the two-man design. The three-man design shown does not affect vehicle dimensions or weight appreciably. Weight, in fact, is reduced from 32.7 to 31.9 tons—the eight extra missiles in the two-man version outweigh the added crew station in the three-man version.

Other three-man versions are also possible, principally by switching to the 25-in. longer MLRS chassis. This gives the commander more leg room, but does not substantially increase effectiveness and does not reduce his exposure to enemy fire or missile explosions. Because of these considerations and the substantially increased vehicle weight, we did not pursue a design based on the MLRS chassis.

HVM LIGHT ARMORED VEHICLE

This is an HVM implementation of the eight-wheeled Light Armored Vehicle, much like that of the HVM Bradley. The main difference is that a smaller number of missiles fit into the LAV's reduced chassis depth. Figures 50 through 55 show the two-man and three-man versions, with 22 and 16 missiles in the chassis, respectively. The main changes to the existing LAV are removal of the turret, rework of the crew stations, movement of the fuel tanks and some drive links, and alteration of the rear cargo doors. The same HVM launch device and mast sensor pod are used as in the HVM Bradley. Again, there is no change to the existing vehicle propulsion, suspension, and armor protection from that of the baseline system.

Two-Man Design

The two-man version appears fairly comfortable, with each crew member having good fore and aft spacing. They can recline somewhat and they have room to the sides for personal articles and rations. The two men are shown with conventional hatches, although the visor-type ones used in the MBT may be employed.

The weight of the two-man HVM LAV increases somewhat over that of the conventional LAV, mainly because of the weight of the missiles. We estimate a modest weight gain of 2.1 tons, from 13.6 to 15.7 tons. The height of the LAV will decrease from 92 to 81 in. The vehicles should be airliftable using either a C-130 or C-141.

Three-Man Design

As can be seen from Figs. 53 through 55, the third man in the HVM LAV is even more cramped than in the Bradley HVM vehicle. He has little room to turn, marginal headroom, and he is wall-to-wall with the missiles. NBC sealing will be more difficult in the three-man configuration, as will sealing against missile plume. Again, the third man will have to work with a subset of displays and controls. On the other hand, the third man will be in a good position for maintenance and repair.

762 MM

72

40°

42°

253

ELECTRONICS NBC

FUEL

FUEL

FUEL
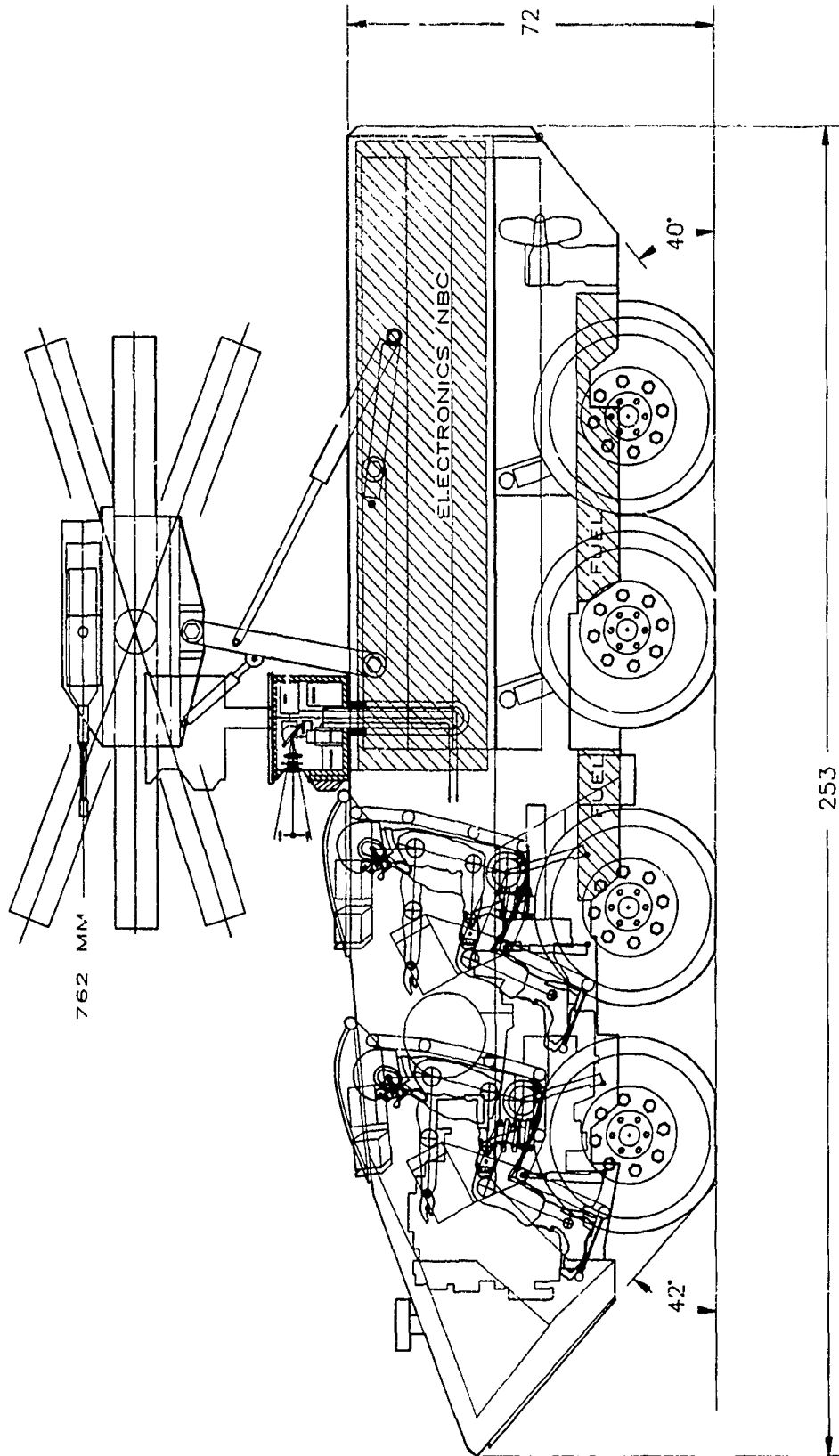
Fig. 50—Two-man HVM LAV: side view
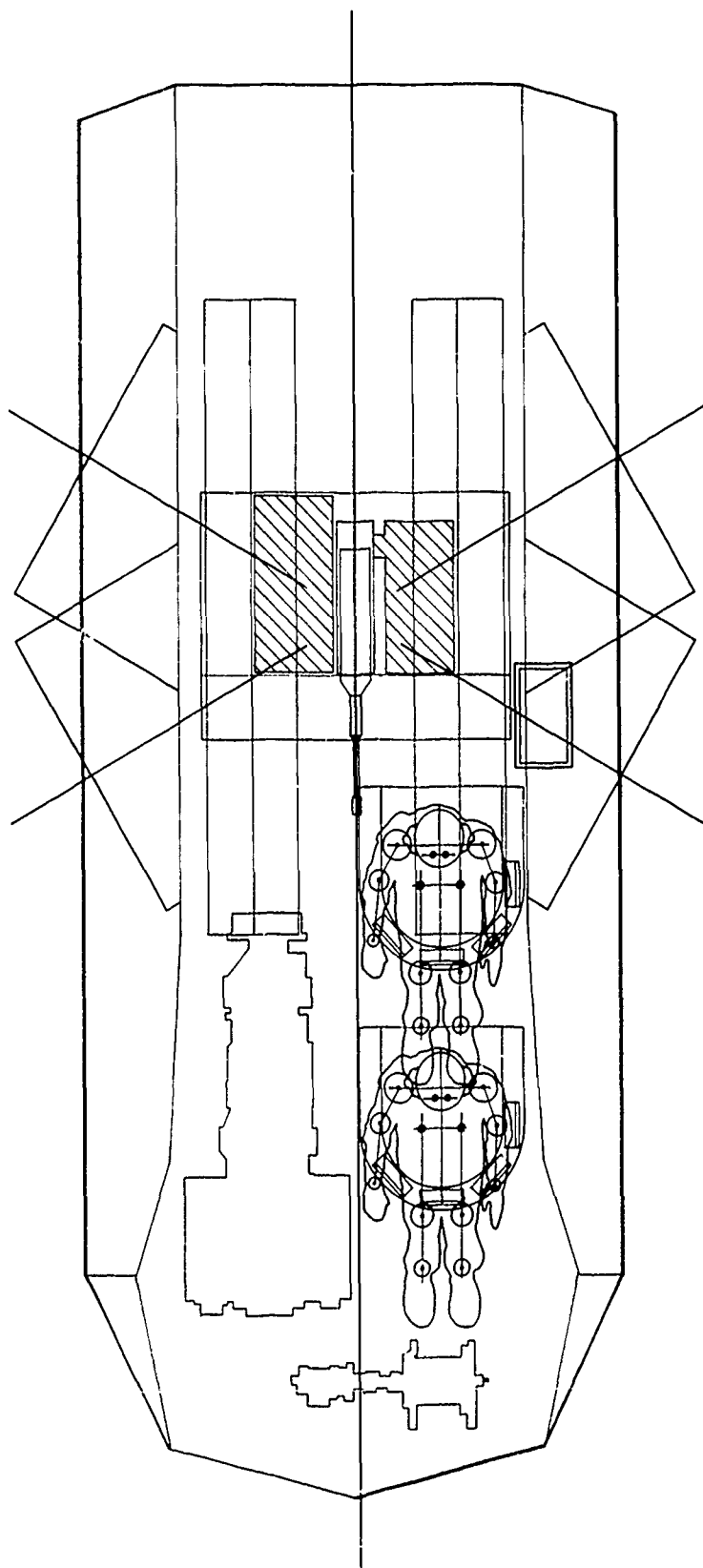
Fig. 51—Two-man HVM LAV: top view
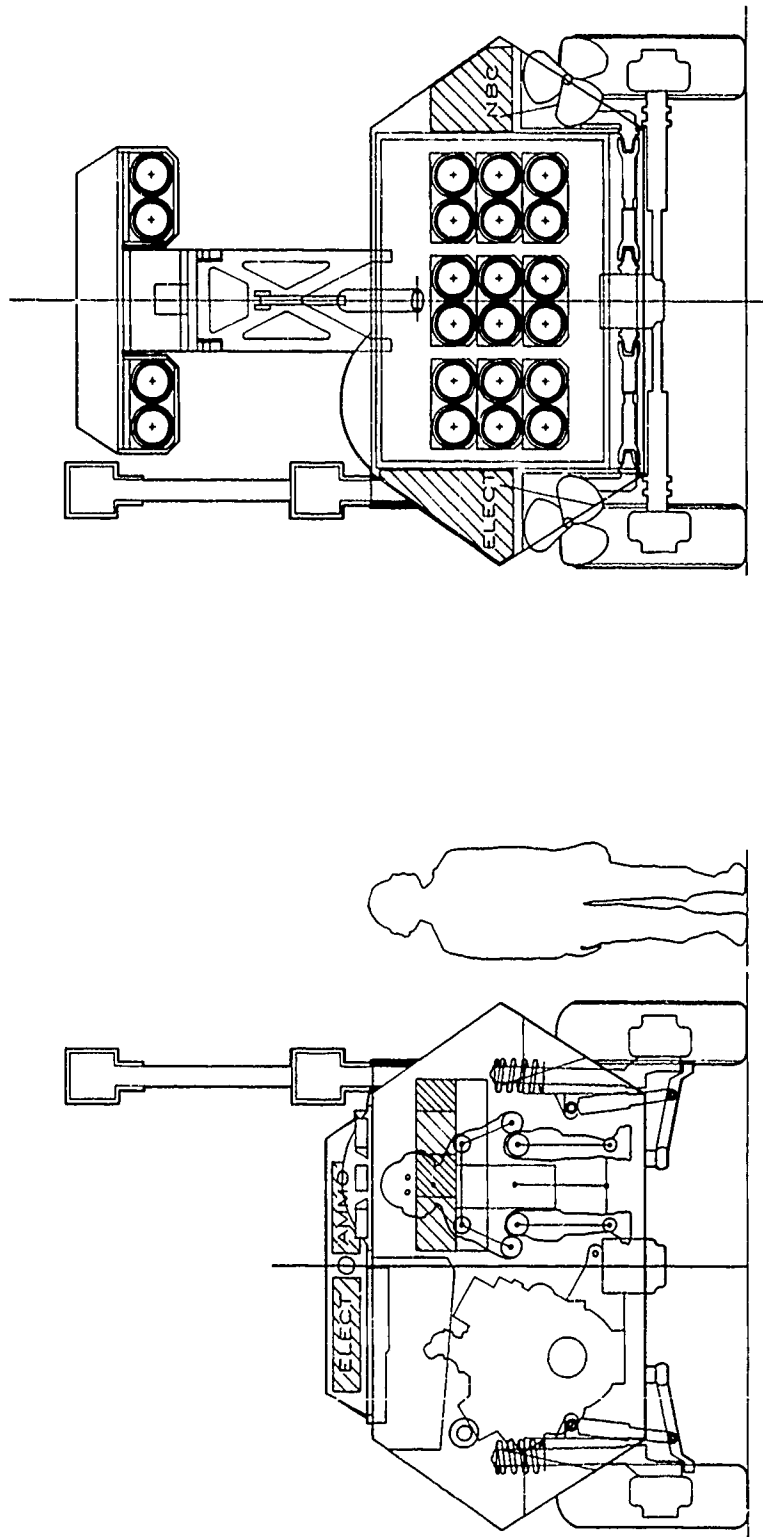
Fig. 52—Two-man HVM LAV: front and rear views
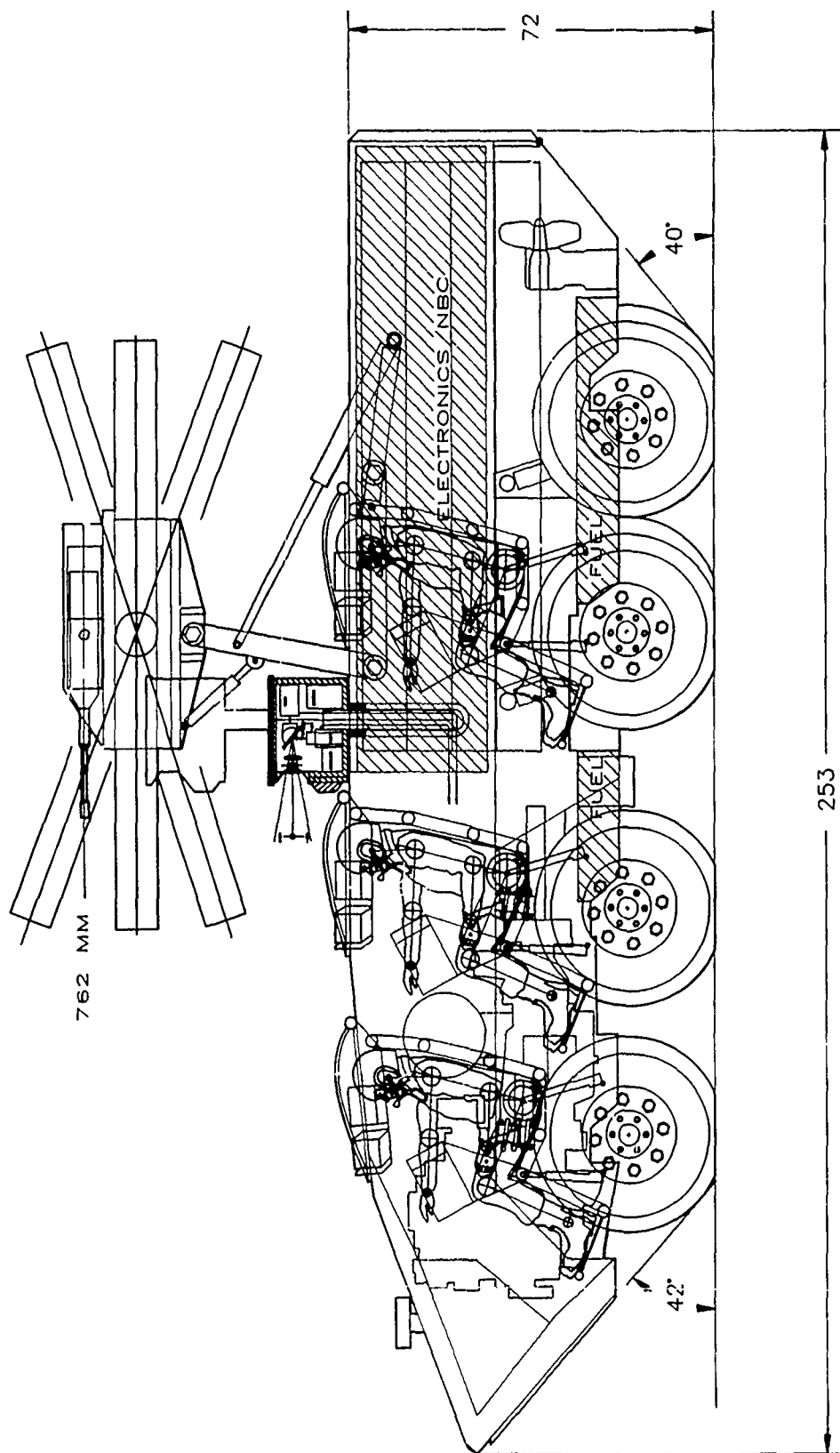
Fig. 53—Three-man HVM LAV: side view
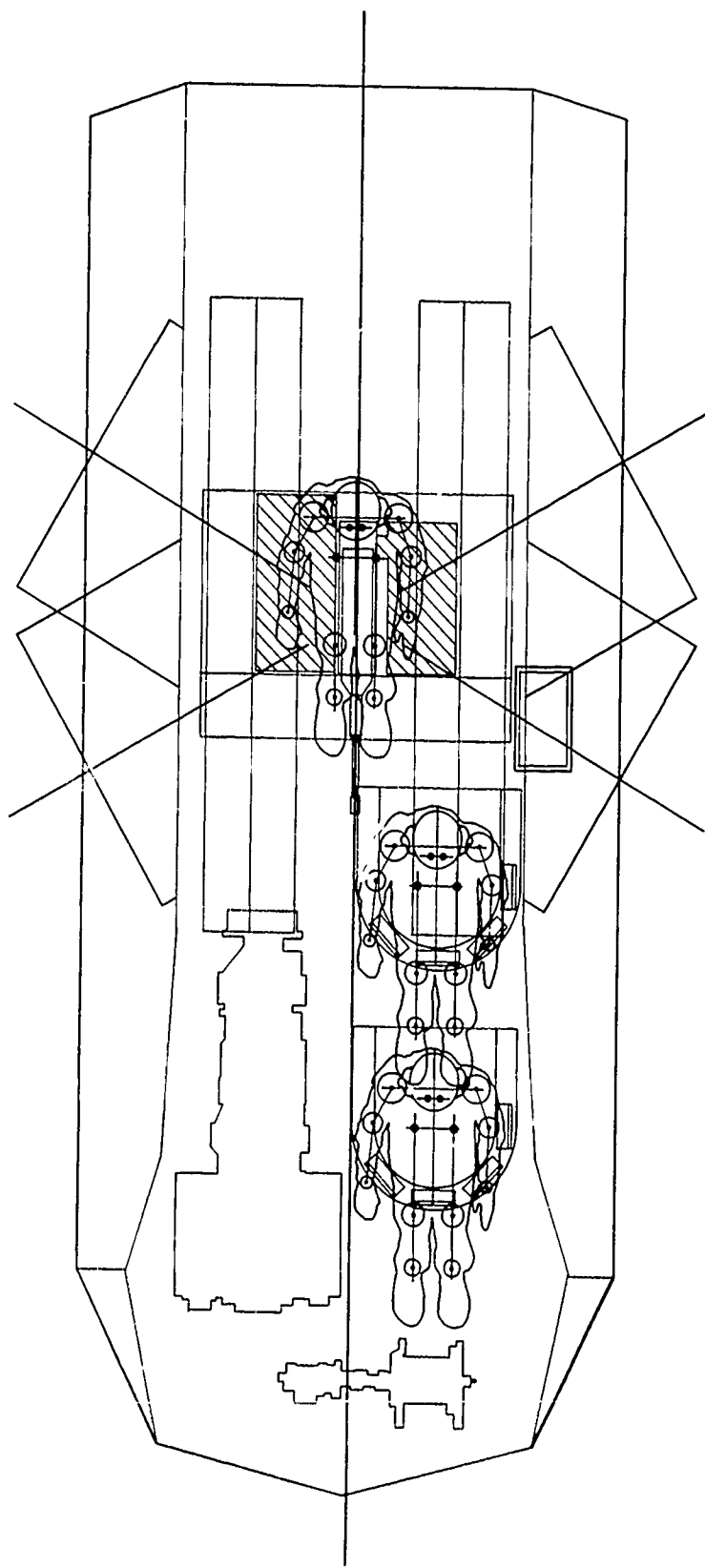
Fig. 54—Three-man HVM LAV: top view
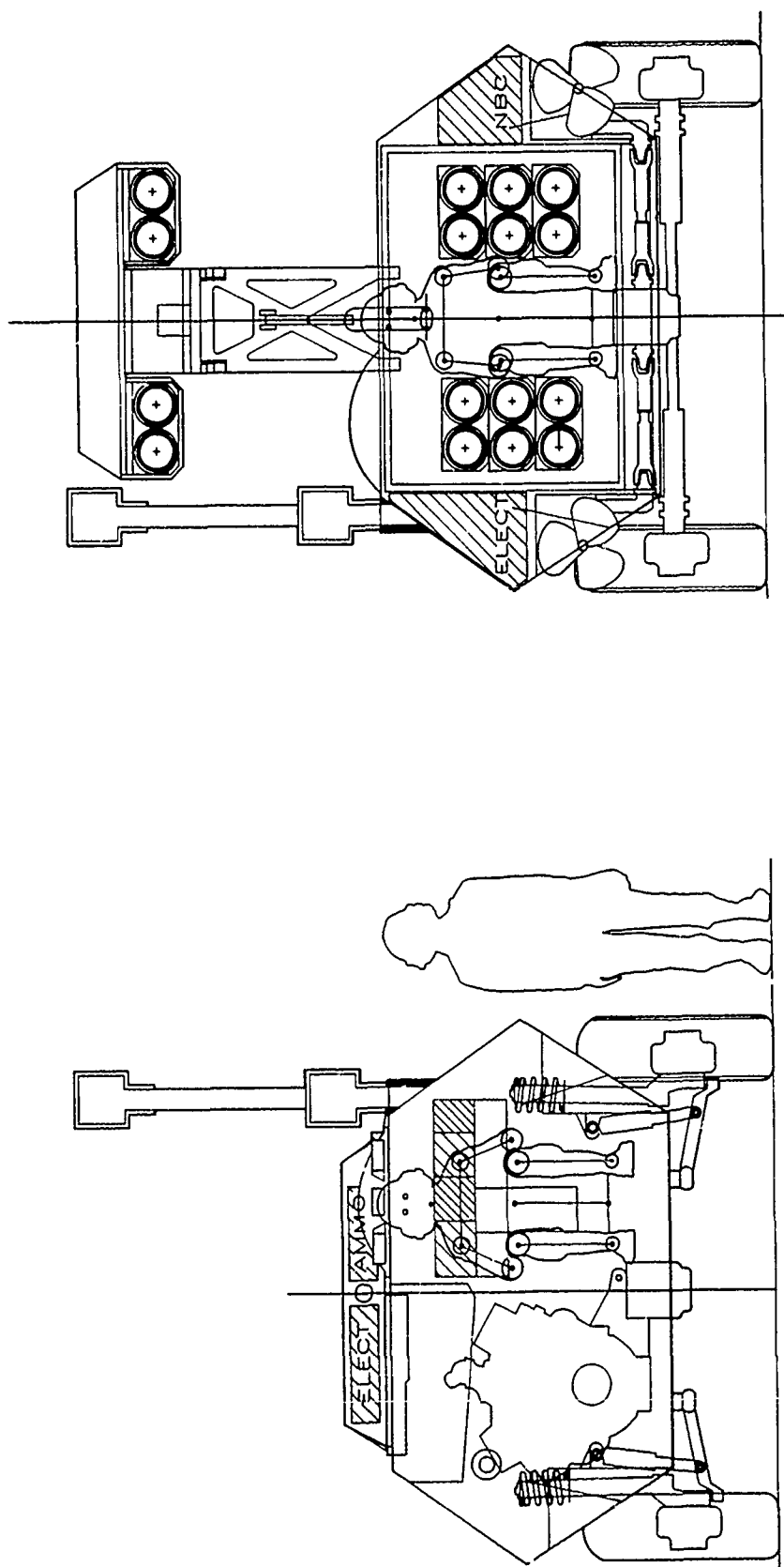
Fig. 55—Three-man HVM LAV: front and rear views

The weight of the three-man HMV LAV should be 600 lb less than that of the two-man vehicle, because crew station weight is less than the weight of the missiles removed. No changes in external dimensions are expected.

CONCLUSIONS

Both the Bradley and LAV appear to be suitable for reduced crew operation and launching of hypervelocity missiles. The Bradley fighting vehicle has somewhat more room and should provide a more stable platform for launching. Even without the stretched chassis of the MLRS, the Bradley provides more space than the LAV for a three-man crew. The LAV, of course, is much more suitable for airlift operations.

It should be noted that neither of these light vehicles is a substitute for a main battle tank. They may be placed in protected defensive positions and used for covering fires against light and heavy systems, or they may be used for long-range direct fires in offensive operations. They do not have the armor protection needed for close engagements, particularly on the offensive.

VI. SIMULATION ANALYSES

OVERVIEW

We used two in-house simulation environments to model the capabilities, dynamics, and tactics of some of our reduced crew tank designs. JANUS was our primary simulation system, covering five scenarios having different combinations of U.S. and Soviet tank designs. RISE, an AI-type simulation, was used to explore techniques for automating such onboard functions as navigation aiding, communication management, situation assessment, and fire control.

Each of the simulation environments contributes in a different way to analysis, and each has its limitations. JANUS is best at large-scale, battalion-level analysis of tactics. It is fast and has good routines for scenario specification and outcome calculation. We ran excursions with combined arms (APCs with the tanks), artillery (self-propelled and towed), FASCAM mines, helicopters, and bispectral smoke. The runs showed the dominance of the tank weapon size, armor level, and firing rate on scenario outcome, except when bispectral smoke was present. Sensor capabilities were not found to be critical in most scenarios because of the rolling European terrain used. The terrain usually hid the attackers until they were relatively close (1–2 km), at which range most sensors could easily spot the threats. Highlights of the JANUS runs are given in the following subsection.

The second simulation, RISE, focused on the problems of modeling onboard automated functions. It also modeled terrain and vehicle movement in a much more detailed manner than JANUS. Its main role was to estimate the technology needs—processing power, memory requirements, network speed, human interface characteristics, and software—associated with each machine function. It was also useful for estimating time delays in the various human and machine operations by automating many of the tactical operations situation assessment and planning functions.

JANUS ANALYSES

We conducted a series of force-on-force analyses with the JANUS tactical simulation environment, evaluating some of the weapons systems candidates in different tactical situations. JANUS is well suited to this task, because it supports modeling of micro-terrain, deployment of forces on that terrain, and engagement of a wide variety of unit types. As described below, we structured a set of representative battle situations using a top-down approach, and then followed a systematic experimental design to pit different U.S. and Soviet force mixes against each other.

JANUS Characteristics

JANUS is an interactive, battalion-level, two-sided game created at Lawrence Livermore Laboratory to explore relationships between combat and tactical processes. It uses a stand-alone, event sequenced, stochastic computer simulation programmed in

FORTRAN. RAND has the TRAC-WSMR version, which was expanded from the Livermore version to focus on ground warfare. As many as 600 combat entities (tanks, APCs, helicopters, etc.) per side can be simulated. The units move over a computer-generated Defense Mapping Agency (DMA) terrain map that can cover 1 to 60 kilometers square. JANUS also models such ancillary aspects as minefields, obstacles, smoke, and dust. Users can either specify preplanned paths for the vehicles, with automated engagement behaviors, or they can play individual units interactively. They interact through four playing stations, each of which shows the friendly forces and those enemy forces that have been sensed. Figure 56 shows a sample screen image depicting forces on both sides.

JANUS models the fighting systems and their interactions in a fairly complete manner. It supports such specialized systems as precision-guided munitions, chemicals, scatterable mines, air defense radars, and different kinds of smoke. It performs line-of-sight calculations, models sensor contacts (using NVEOL algorithms), calculates movement speeds, simulates weapon performance, accounts for ammunition, and characterizes supply/resupply performance. The data used for these functions can be interactively reviewed and changed by the user, using menu-driven editing utilities. These utilities allow input, modification, and review of terrain, scenario, system, and weapon.

In most of our operations, we concentrated on the preplanned behavior mode of JANUS. This reduced the variability of runs, so that system characteristics could be compared most effectively.

Specification of Tactical Scenario

We defined a set of five tactical vignettes by first developing an overall battle context and isolating the five constituent vignettes. In this top-down manner, we can show how each vignette fits into the overall picture and maintain consistency between elements. We call the larger view of battle a scenario. Within the scenario, the vignettes are combat missions that reflect key aspects of the overall battle. We use each of the tactical vignettes to test our candidate technologies and force mixes.

The overall scenario we examined was extracted from a theater campaign plan for the first few days of conflict in Central Europe. From that plan, we developed the concept of operation for a selected Warsaw Pact (WP) front and its subordinate armies. Concurrently, we developed the concept of operation for the opposing U.S. forces. The WP front concept of operation involved an attack by two first echelon armies against a defending U.S. corps, with a second echelon WP army positioned to exploit a breakthrough in the main attack sectors.

The Blue planning assumption was that the corps was unsure of the direction of the WP main attack, but estimated that it would be in the northern portion of the corps sector. The corps chose to defend with a division and a brigade in prepared positions, along with one and two-thirds divisions in positions from which they could conduct a large-scale counterattack in the corps sector. Blue positioning of forces was postulated on the assumption that the attacking WP forces could be attrited and contained because of Blue terrain advantages.

In the operation, Red's attack by two first echelon divisions in the northern Blue sector was stalled, but Red did achieve a breakthrough in the southern corps sector against the defending Blue brigade. Additionally, Red attempted to conduct a flank attack against the
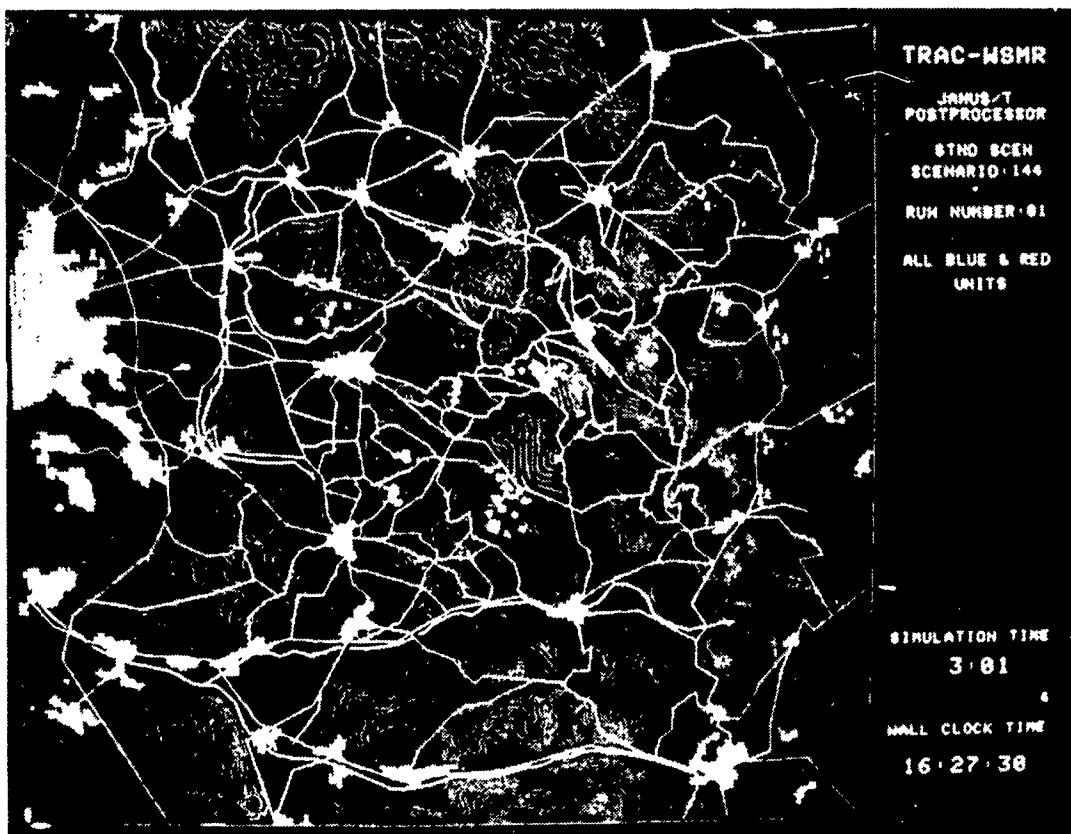
125

Fig. 56—JANUS screen image

northern corps sector in the area left open by the penetration of the southern sector. The overall concept for the operation is shown in Fig. 57.

Tactical Vignettes

Each of the five high-resolution vignettes was taken from the overall concept of operation, at a level several echelons down from the top. First, Red front and army plans for division zones of operation assign areas of responsibility to the regiments. The regiments in turn specify boundaries for subordinate units such as battalions and companies. It was from these lower-level plans that the high-resolution vignettes were chosen. The plans are titled by mission in the descriptions below.

Blue Defense Short Range (BDS). One Blue company is defending from its primary battle position against two Red battalions attacking abreast, as diagrammed in Fig. 58. The Blue objective is to delay and attrit the advancing enemy forces by occupying commanding terrain. In those excursions that provide additional assets, Blue will canalize the enemy forces with antitank ditches, FASCAM minefields, helicopters, and artillery. Blue may also have to overcome an enemy bispectral smoke barrage. Terrain was chosen for battle positions that allowed detection ranges normally less than 3 km.

Blue Defense Long Range (BDL). This vignette, shown in Fig. 59, occurs to the south of the BDS engagement. It differs in that terrain was chosen that allows detection ranges normally greater than 3 km. One Blue company is defending from its alternative prepared battle position against two Red battalions attacking abreast. The objective is now to prevent a breakthrough into the city—by engaging the enemy vehicles at long range, disrupting an enemy river crossing, and then mounting a holding action to permit counterattack by Blue's main forces.

Blue Counterattack Short Range (BCS). One Blue battalion counterattacks a Red company on the right flank of a Red battalion in hasty defense. Terrain was chosen that provided detection ranges generally less than 2 km. As shown in Fig. 60, the objective was to outflank the enemy penetration by achieving local superiority. In those excursions with additional assets, the Blue forces will also soften enemy defenses with artillery, destroy and overrun the enemy defenses with ground maneuver and close air support, and use smoke to offset Red's terrain advantage.

Blue Counterattack Long Range (BCL). In this vignette (Fig. 61), one Blue battalion counterattacks a Red on the right flank of an attrited Red battalion in hasty defense. Unlike BCS, terrain was chosen that provided detection ranges of about 5 km. The objectives are more ambitious than in BCS: Blue attempts to attack and seize the enemy strongpoint by establishing a bridgehead across the river, executing a frontal attack with two companies, and mounting a flanking attack with one company. The final objective is to secure high ground for passage of friendly following forces.

Red/Blue Meeting Engagement (ME). This vignette (Fig. 62) is taken from late in the overall operation. One Blue battalion spearheads the deep assault to cut off the Red second echelon forces. They use terrain to mask their movement, and both sides experience tactical surprise because their reconnaissance elements had not established contact due to intense artillery fire, air attacks, and disrupted movement along the route. In an even battle, the
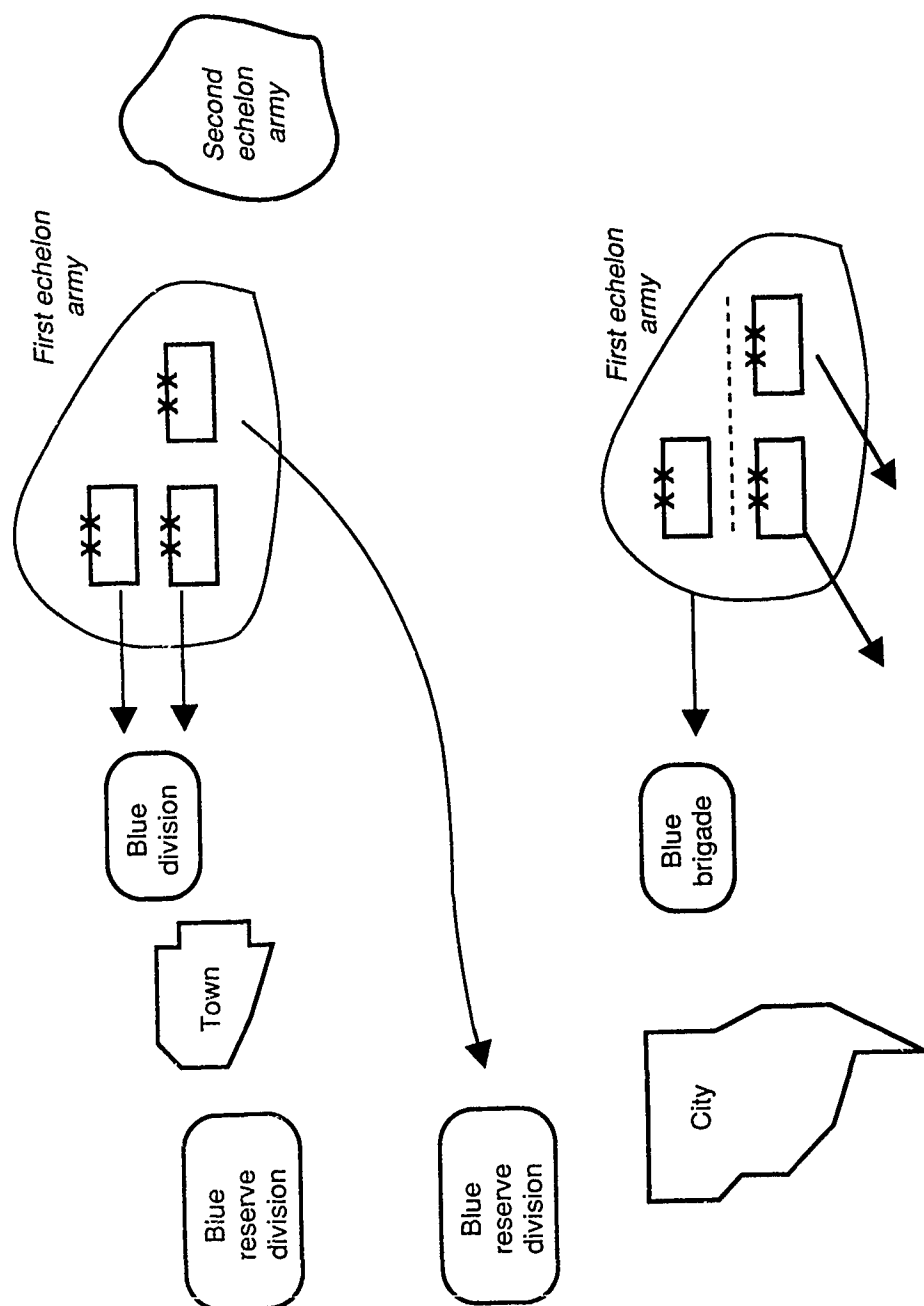
Fig. 57—Overall concept of operation
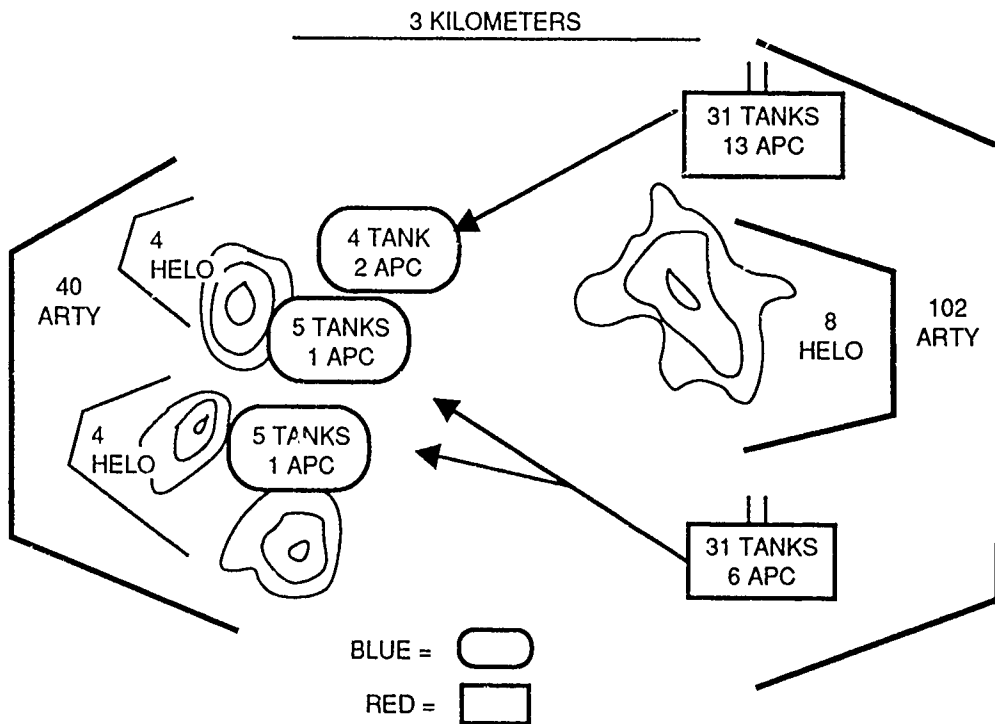
Fig. 58—Blue defense short range vignette
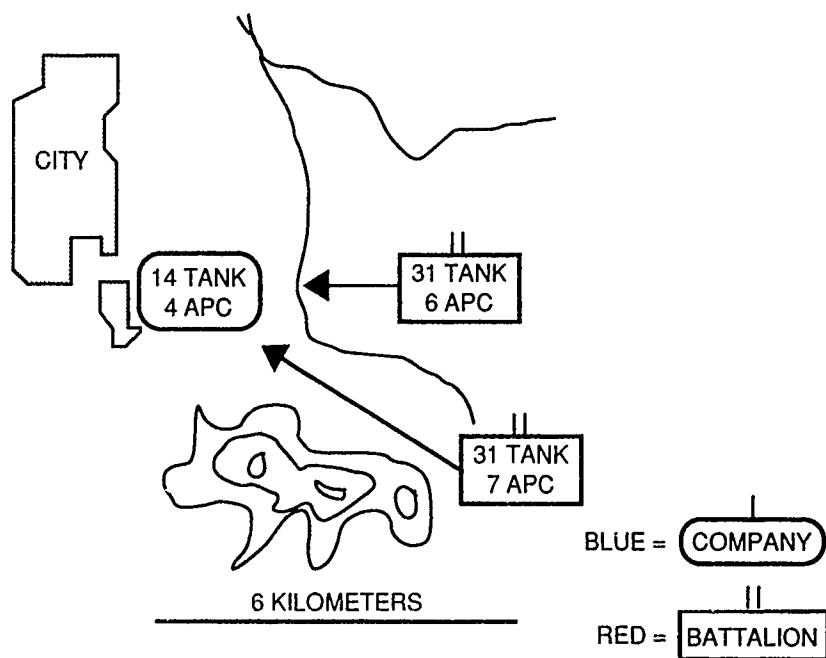
Fig. 59—Blue defense long range vignette
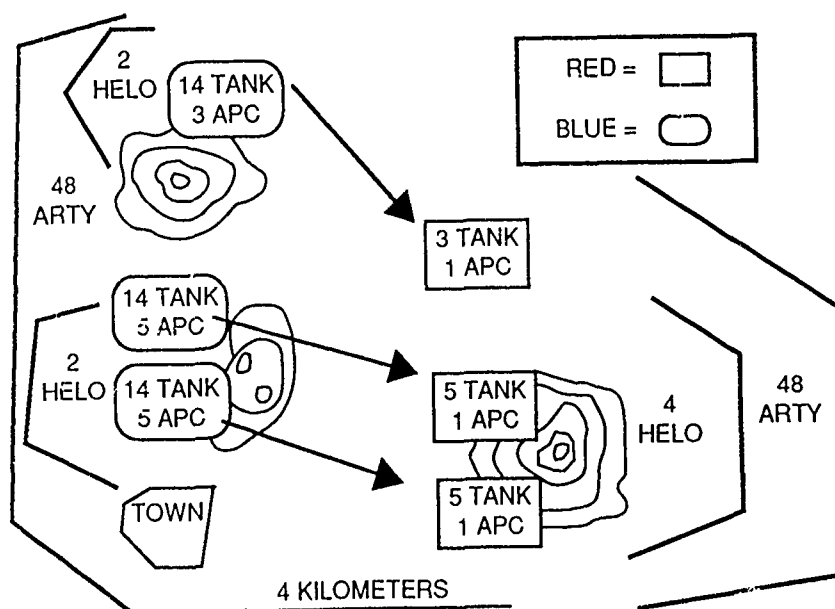
Fig. 60—Blue counterattack short range vignette
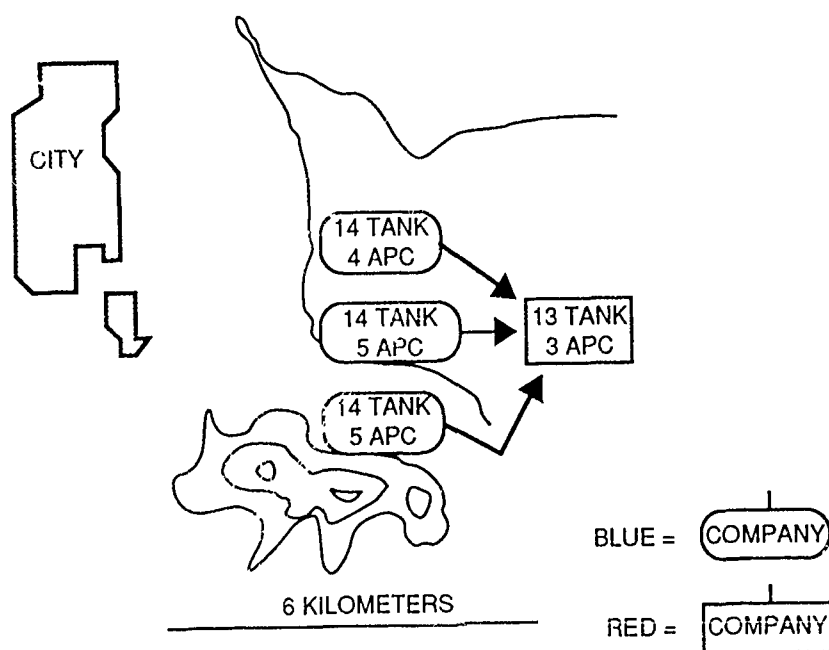
Fig. 61—Blue counterattack long range vignette
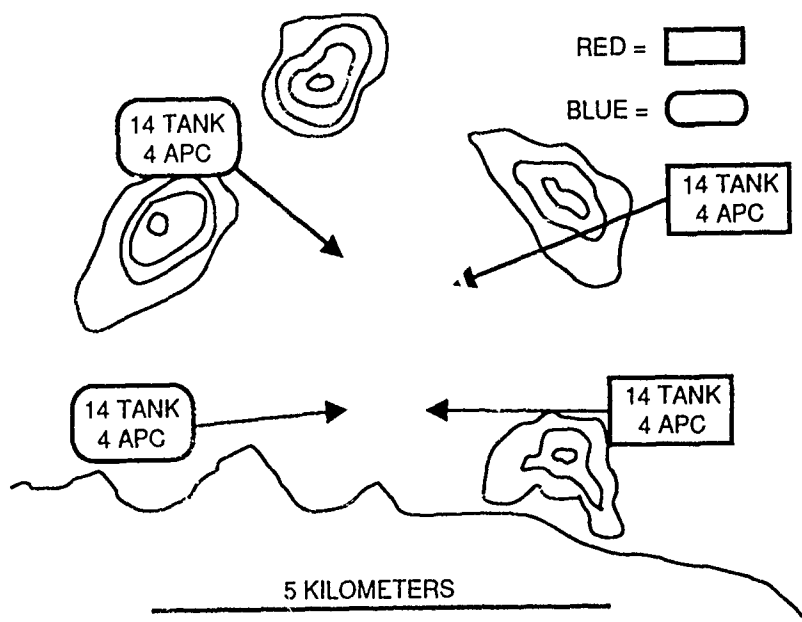
Fig. 62—Red/Blue meeting engagement vignette

leading Blue company engages the Red company-sized advance party of the leading second echelon regiment. Detection ranges in this vignette were about 2 km.

Experimental Design

We developed a systematic design that involved key combinations of Red and Blue weapons systems, the five engagement vignettes, and five force augmentation excursions (APCs, artillery, FASCAM, helicopters, and bispectral smoke). We then examined such outcomes as detection ranges, kills, and loss exchange ratios (the LER is the ratio of Red systems killed to Blue systems killed).

We ran four key combinations of Red and Blue weapons systems. They were all in the form of pure tank forces, characterized by such parameters as armor level, main gun muzzle velocity, sensor complement, and reload time. Each of the combinations was run under all five scenario vignettes. The four combinations were:

M1-A1 vs. M1-A1   This is a calibration run of current issue Blue tanks (with generic MBT characteristics) engaging each other. The intent is to determine relative tactical and terrain effects separate from the equipment.

M1-A1 vs. T-80	The current Blue MBT faces a generic current Soviet MBT.
M1-A2 vs. Adv Red MBT	An improved turreted Blue MBT against an advanced turreted Red MBT.
RCV vs. Adv Red MBT	The advanced reduced crew (two-man) Blue MBT against the advanced Red MBT.

Other combinations, such as M1-A1 vs. Adv Red MBT and RCV vs. T-80, were not run because of time constraints and because these combinations were not deemed critical.

After the pure tank runs, we augmented the tank forces with armored personnel carriers on both sides. All combinations of five vignettes and four equipment pairings were run under this combined arms condition.

The force augmentation excursions (with artillery, mines, helicopters, etc.) were, finally, run under four combinations of equipment pairings and vignette:

- BDS with M1-A2 vs. Adv Red MBT
- BDS with RCV vs. Adv Red MBT
- BCS with M1-A2 vs. Adv Red MBT
- BCS with RCV vs. Adv Red MBT

Only the short-range versions of the Blue defense and counterattack scenarios were run with the excursions because the long-range vignettes with these conditions were already one-sided for the defense. Addition of artillery and air assets would only have made them more one-sided. Also, no excursions were made with the meeting engagement, because its short duration precluded the possibility of using artillery or aviation.

The force excursions were cumulative. First APCs were added to the basic combined armed force and run under the four equipment/vignette combinations. The augmented tank forces were given artillery—both improved conventional munitions (ICM) and high explosives (HE)—and then run under the four combinations. The FASCAM scenario switched some defensive batteries from firing artillery rounds to delivering mines. The close air support excursion ran all these conditions and added attack helicopters firing ATGMs. The final excursion added artillery-delivered bispectral smoke by the attacking side.

Experimental Outcomes

For each of the vignettes, we describe below how the engagement unfolded, present summary statistics, and draw preliminary conclusions. After all the vignettes have been covered, we make overall observations about the weapons systems and force mixes.

Blue Defense Short is a short range vignette that takes place in terrain with rolling hills near the town of Fulda in southern Germany. The baseline version has a Blue company of improved Blue MBTs reinforced with armored fighting vehicles (AFVs) in defensive position.

They are arrayed against two battalions of attacking advanced Red MBTs. The vignette typically runs about 20 minutes, at which time Red either controls key territory or sustains excessive losses and terminates the engagement. We first describe the baseline case and then cover the many excursions. In each case, a typical scenario from the ten normal stochastic repetitions is described.

With the baseline case, M1-A2 vs. Adv Red MBT, the battle develops quite slowly. The two Red armored battalions first move into assault formation in the northern and southern areas to attack Blue positions in the center. Red is well protected by terrain in the north as it moves through the city and across the river. The Red battalion in the south is sporadically visible due to the rolling nature of the terrain. The situation was diagrammed earlier in Fig. 61. The first kill occurred in the southern area at about four minutes, when a Red tank was destroyed by a Blue AFV at a range of three km. There was little combat in the first ten minutes, with a total of only three Red vehicles lost. At approximately 11 minutes, the Red battalion in the north moved into the valley and was detected en masse by Blue. The first Red casualty in the northern area was recorded at this time, after Red had moved within two km of the Blue position. At 16 minutes, Red had come within one km of the Blue position, causing Blue to withdraw. Red forces were now at about 50 percent strength. A firefight soon erupted in the northern area and continued for the next several minutes. Rapid, multiple engagements occurred, and Red sustained significant losses. There were sporadic fires in the south, but it was still relatively quiet. By 15 minutes, things had cooled off in the north, as the Red force had been largely depleted. The pace of battle was now heating up in the south, with Red sustaining casualties at a high rate.

The distribution of kills in this vignette was different for the Red and Blue sides. On the Blue side, the M1-A2 accounted for about 90 percent of the kills but only 80 percent of the losses, indicating that it had a higher specific LER (loss exchange ratio, the number of enemy systems killed divided by the number of own systems killed) than the AFV. For Red, the marginal contribution of AFVs was significantly higher. Red AFVs accounted for about 16 percent of the kills but only 6 percent of the losses, resulting in a specific LER more than twice that of the Red tanks.

Our first variation on this scenario involved substituting the RCV with its increased firepower and armor for the M1-A2. Again, only a few engagements took place in the first ten minutes. At 11 minutes, the Red battalion in the north emerged from terrain coverage and moved into open fields of fire. A major firefight ensued, continuing for the duration of the vignette. Battle began in the southern area at about 15 minutes and was of similar intensity. The superior firepower and armor of the RCV was quickly evident, as it destroyed a large number of enemy vehicles and sustained few losses. Detection and engagement ranges were very similar to those in M1-A2 vs. Adv Red MBT. With the RCV, the contribution of AFVs for Blue was even further reduced, as they accounted for all Blue losses and only 10 percent of the total kills. The contribution of Red AFVs increased substantially against the RCV force, accounting for half the Red kills (mostly Blue AFVs) and only 10 percent of the losses. Comparisons of the effectiveness of M1-A2 and RCV (tank force kills only) are shown in Fig. 63.

The defensive terrain advantage itself is shown in the M1-A1 vs. M1-A1 calibration run. The first excursion with this vignette was indirect fires (IF), performed with the M1-A2 vs.
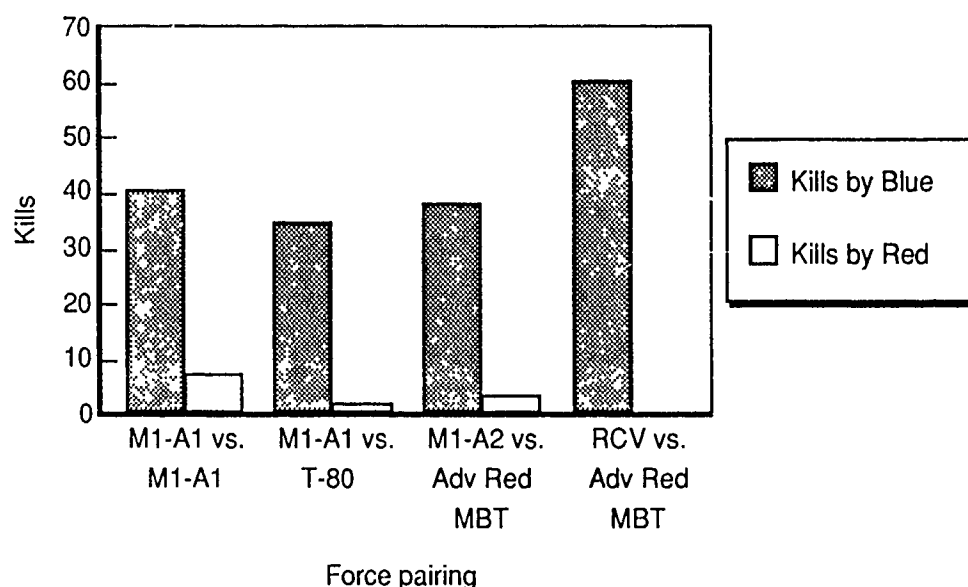
Fig. 63—Tank force kills, Blue defense scenario

Adv Red MBT and RCV vs. Adv Red MBT pairings. Artillery was added to both sides, with Red having a quantitative advantage of approximately 2.5 to 1. Red artillery strikes were concentrated on Blue positions and continued through most of the battle. Blue artillery was concentrated on the avenues of approach about 2.5 km in front of the Blue position. The character and progression of the battle was largely the same as in the baseline BDS vignette. Artillery kills were sporadic and few, averaging only 2.4 per run. Artillery was harder on Blue, accounting for about 20 percent of Blue losses. In contrast, it was responsible for only 1 percent of Red losses. This led to a decline in Blue's advantageous LER over Red. Also, for both Red and Blue, the relative contribution of AFVs declined substantially—probably a reflection of the greater vulnerability of AFVs to artillery. For Blue, AFVs accounted for about 8 percent of kills, a decrease of 2 percent from the original excursion. Blue AFV losses were constant as a percentage of the total, about one quarter. On the Red side, AFV kills were once again about 25 percent of the total, but losses increased from 6 to 10 percent of the total. Perhaps the most significant effect of artillery was in decreasing the acquisition and engagement ranges. Dust and suppression cut ranges by 35 and 20 percent for Blue. Red detection and engagement ranges were reduced by 10 percent, for similar reasons.

When artillery was added to the RCV vignette, results were quite similar. The character and progression of the battle were virtually identical, with artillery losses again sporadic and few. The value of artillery was found to be primarily in disrupting the enemy systems, killing a few AFVs, and then effectively preventing long-range detections and engagements. Detection ranges for Blue were reduced by 30 percent, with a 10 percent reduction for Red. Firing ranges were off 10 percent for Blue and 5 percent for Red.

Our next excursion with the BDS vignette was FASCAM, in which two batteries of Blue artillery switched from firing improved conventional munitions to FASCAM scatterable mines, laying a 1-km rectangular minefield about 2 km in front of the Blue defensive positions. Surprisingly, the course of battle was virtually unchanged from that of the pure ICM excursion. FASCAM appeared to be a poor tradeoff for ICM in the M1-A2 vs. Adv Red MBT runs, as it failed to slow enemy vehicles and proved less lethal. Detection, engagement, and kill ranges on both sides were identical to those in the ICM excursion. Red/Blue LER declined somewhat, because of a decrease in Blue artillery kills. The roles of AFVs were roughly the same as in the pure ICM runs. Also, no major differences were seen with the RCV runs.

The Close Air Support (CAS) excursion was more interesting, adding eight Red helicopters and four Blue helicopters. The Blue helicopters were superior to Red ones, having advantages in both sensors and munitions. The helicopters arrived on station at two minutes game time, shortly before the main engagements began. The Blue helicopters took up a position approximately 2.5 km behind Blue positions, whereas Red helicopters were 3 km in front of them.

The course of battle was similar to the previous excursions, but the timing was accelerated. The helicopters detected and engaged at much longer ranges (4.5+ km), taking kills away from ground systems. The Red/Blue LER was increased slightly, because the Blue helicopters had a higher specific LER than the accompanying ground systems, thus increasing the overall average. In fact, Blue's average detection and engagement ranges were increased more than 50 percent, while Blue kill ranges were twice as long as they had been. This was due to the superior sensors, vantage point, and weapons range of the helicopters. Detection ranges for Red were improved by 150 percent, engagement ranges were increased by 35 percent, and kill ranges were doubled.

In this CAS excursion, the distribution of kills and losses was quite different from that in previous excursions. For Blue, the relative contribution of AFVs was almost the same, with similar results in terms of both kills and losses. The number of kills by tanks was decreased by 20 percent, indicating that helicopters were taking kills away from tanks. This result is to be expected given the long range of air-launched ATGMs. Tank losses were decreased by about 30 percent. Helicopters proved extremely effective, increasing the total number of Blue kills by 50 percent. In addition to the ten kills taken from tanks, they provided 22 new kills. Helicopters were quite vulnerable, however, losing half their force in each run. The specific LER for Red and Blue helicopters was only slightly higher than that of tanks.

Addition of helicopters to the more capable RCV force proved less of an enhancement. The character and progression of battle became similar to that of the indirect fires excursion. Helicopters took kills from RCVs, but provided little marginal gain. Total LER was decreased somewhat, because the Blue helicopters exhibited a specific LER lower than that of the ground systems, dragging the overall average down. Red helicopters, on the other hand, proved a far greater marginal benefit. Red helicopters took a few kills from tanks, but primarily provided new kills. Total Red kills were almost doubled.

The bispectral smoke (BSS) excursion was the most dramatic. Here Red shifted three batteries of artillery from firing HE to firing bispectral smoke. A heavy cloud was laid on top of all three Blue positions, and the progression of battle became radically different. There

were essentially no engagements through the first 12 minutes, with only one Red vehicle detected and killed. At 12 minutes, Red had progressed to within 200 meters of Blue's position in the north, and within 400 hundred meters in the south. At 13 minutes, Red moved within 100 meters of Blue in both north and south. Close-in engagements began, systems were virtually bumping into one another, and Blue was overrun. There were few casualties on either side, with exchange ratios roughly even. Helicopters were uninvolved to this point. By 16 minutes, the Blue position in the north was destroyed, whereas the ones in the middle and south were severely depleted. At 18 minutes, Red forces rolled through the smoke cover, behind the Blue position, and were engaged by Blue helicopters at ranges of 2.5 tp 3 km. From 19 through 24 minutes, Blue helicopters engaged Red forces, destroying most of Red armored systems. Battle was stopped at 26 minutes.

Surprisingly, detection and engagement ranges for Blue were similar to those in the previous excursion, because the long-range engagements of helicopters (after Red overran the smoke cover) made up for the extremely short (less than 100 meters) engagements of the armor systems in the smoke. Red detection ranges were reduced by 50 percent, with firing and kill ranges some 70 percent lower. Red helicopters were essentially eliminated as a factor by the smoke. Blue helicopters, however, were quite effective, accounting for 75 percent of the kills. Due to the loss of visibility, Blue tank and AFV kills were decreased to a fraction of previous levels, while losses were several times what they had been. Introduction of smoke completely offset the terrain advantage of the Blue defensive position, and the performance of Blue ground systems suffered accordingly. Because Blue helicopters engaged enemy units after they moved out of the smoke, their performance was not adversely affected. Red tanks and AFVs also proved more effective than in earlier excursions, because they were able to maneuver within a few hundred meters of Blue without being detected.

Use of the RCV in bispectral smoke did not change the outcomes markedly. This might be expected because the RCV did not have MMW radar and was blinded like the other systems. Blue detections and engagements were both decreased by 75 percent, whereas the number of kills was 60 percent less than under the previou CAS excursion. Again, the detection ranges were decreased by only about 20 percent, because of the helicopter engagements following the Red overrun of Blue positions. Figure 64 summarizes the distribution of kills for each of the excursions.

Blue Defense Long (BDL) is a long-range vignette involving the same force structure as BDS, with Red consisting of two reinforced battalions and Blue having one reinforced tank company. Blue is in defilade on the southeastern outskirts of Fulda, while Red is aligned in company formations about 5.3 km to the east, both north and south of the river (see Fig. 59). Only the baseline conditions involving M1-A2 and RCV are run with this vignette.

The long sight lines gave the defensive forces a great advantage. By four minutes, Red had moved within 4 km of Blue and was about to be detected. At eight minutes, Red had moved within 3 km of the Blue position and there were sporadic long-range engagements, with Blue losing one AFV. By nine minutes, the battle had begun, building slowly with about three kills per minute. Fighting was primarily concentrated to the north of the river, as Red forces were significantly attrited from minutes nine through 15. Through this time, Blue sustained virtually no casualties. The fighting shifted to the central and southern areas at 15 minutes, as the Red force in the north was destroyed. Battle continued at a moderate pace through 25 minutes, with Red sustaining casualties approximately ten times those of
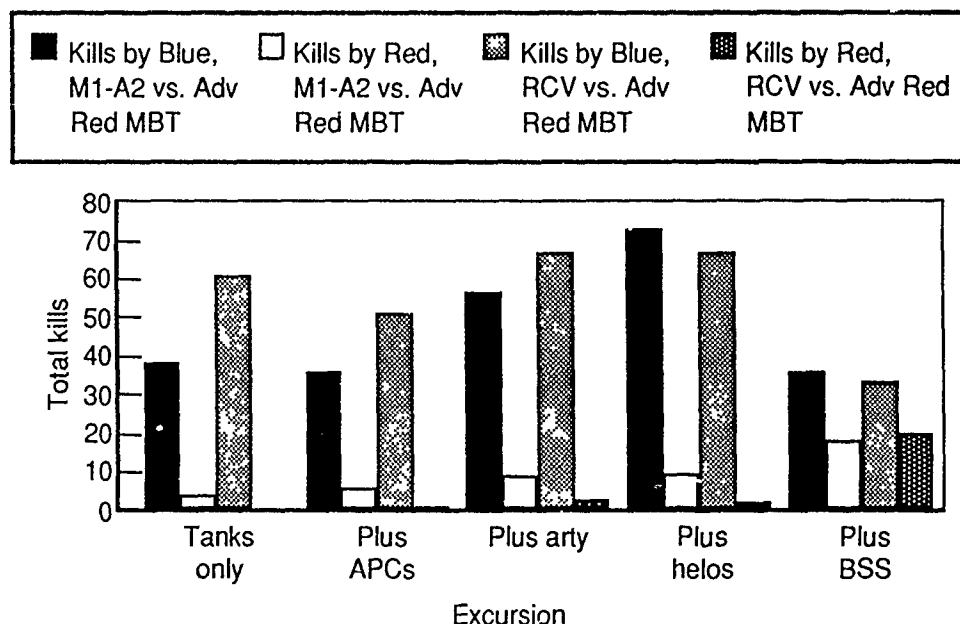
Fig. 64—Total kills by excursion in the Blue defense short scenario

Blue. The battle was stopped at 26 minutes, as Red moved within 1 km of Blue. At this point, Red was at 35 percent strength; Blue was at 70 percent.

The pace and progression of combat using the RCV in BDL was even more one-sided than with the M1-A2. The RCV was able to destroy more enemy systems while enduring few losses. This was seen in its extremely high LER of 21:1, compared to 5.9 for the M1-A2. At the close of battle, Red was at 25 percent, whereas Blue was about 90 percent of its original force strength. The defensive dominance made it unlikely that the other excursions (except bispectral smoke) would have significant effects.

Blue Counterattack Short (BCS) range vignette involves three Blue companies coming out from behind terrain cover and simultaneously attacking a Red company position (Fig. 61). The northern Blue company maneuvers around a hill and through the city. The central company moves through the forest, and the southern company comes over a broad hill. All Blue forces start about 2 km from the Red position. We ran all excursions with this vignette—indirect fires, CAS, and BSS.

In many ways, this vignette was a complement of BDS, with heavy losses of the attacking forces. At two minutes game time, Blue forces were engaged across the front. A firefight developed as Blue and Red engaged in rapid fires along multiple axes. Battle continued at this pace for a few minutes, as Blue forged forward to within 1 km of the Red position. Blue sustained losses of six armored systems for every enemy vehicle destroyed. The simulation was stopped at six minutes, when Blue forces had come within 800 meters of the Red position, triggering a Red retreat. Blue forces sustained loss rates of about 60 percent, while Red was down to approximately 50 percent strength.

The pace and progression of the BCS vignette with RCVs was largely the same as with M1-A2s. The superiority of the RCV in terms of armor and firepower was reflected in the fact that its loss exchange ratio was several times better than that of the M1-A2 for this scenario (Fig. 65).

In the indirect fires excursion of BCS, both Blue and Red added seven batteries of artillery, totalling 48 tubes or launchers on each side. Artillery kills were infrequent, with less than one per side in each run. Progression of the battle was identical to the standard counterattack (BCS) vignette, with similar detection, engagement, and kill ranges. Artillery was somewhat harder on Blue, leading to a decline in its LER. This result is to be expected as Red was in defilade and in a forest, whereas Blue was vulnerable, moving in tight formation in open terrain. The relative contribution of tanks and AFVs for Blue was quite similar to that in the BDS vignette, with AFVs accounting for one quarter of the losses and only 8 percent of the kills. For Red, the contribution of AFVs decreased substantially, with AFVs making up 25 percent of losses and under 6 percent of kills. Artillery was not a factor in changing detection and engagement ranges (as it had been previously), probably because of the short-range terrain. Because forces started out only 2 km apart, there were no long-range detections or engagements to disrupt.

The performance of the RCV in the indirect fires excursion was virtually identical to its performance in the original BCS vignette. Detection and engagement ranges were almost the same as they had been. The LER for Blue declined, as Red artillery proved more effective than Blue.

Fig. 65—Tank force kills in the Blue counterattack scenario

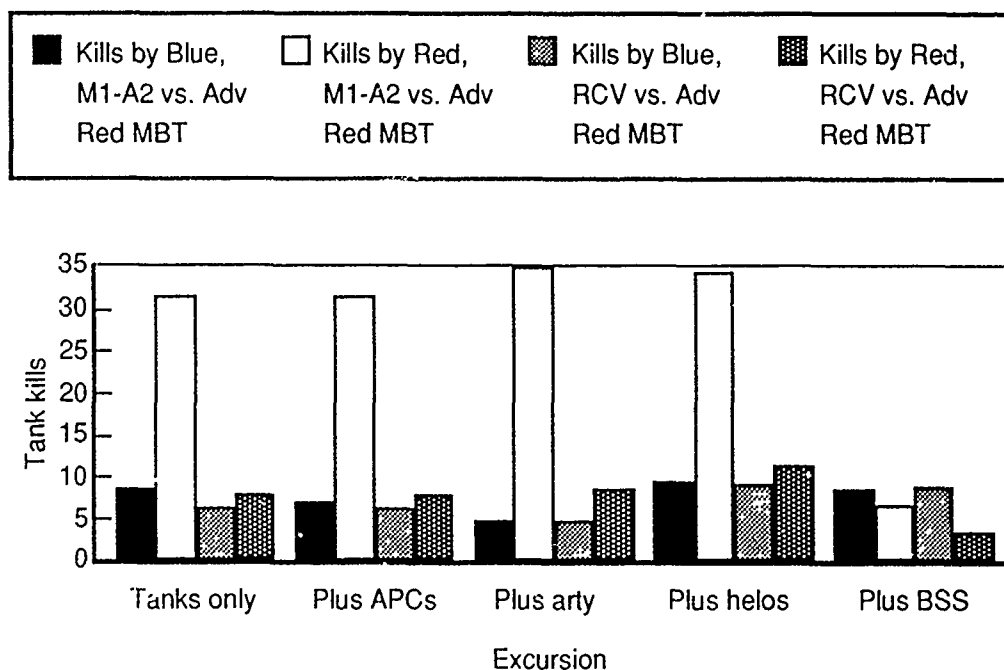In the Close Air Support excursion, four attack helicopters were added to both Blue and Red. The Blue helicopters were deployed 2.5 and 4.5 km east of the Red position. Red helicopters were about 2 km behind the Red position. The helicopters came into the battle at about two minutes game time, and their addition caused little change in the pace or course of battle. Most of the engagements took place between two and five minutes, and all Red helicopters were lost by three minutes game time. In contrast, three of the four Blue helicopters survived and contributed throughout the engagement. In fact, the overall LER was double that of previous excursions, indicating the value that helicopters added to the Blue force. The addition of helicopters also changed the distribution of losses and kills. The Blue helicopters added less than two kills per run, but enabled tanks to almost double their number of kills, creating a combat synergy. For Red, on the other hand, helicopters took away a few kills from tanks, leaving Red with the same total. Half the Red helicopters were killed in the course of battle, decreasing the overall LER significantly. As with the BDS vignette, Blue detection ranges were increased 100 percent, engagement ranges were up 35 percent, and kill ranges were 80 percent higher. These increases are primarily due to the superior stand-off range, sensing, and firepower of the Blue helicopters. Detection, engagement, and kill ranges for the Red force were increased only 10 percent, indicating the far more limited role that Red helicopters played in the excursion.

When the RCV was used in the Close Air Support excursion, the progression and time-lines of the excursion were essentially identical to those in the M1-A2 run. The LER increased by 80 percent, less than that with the M1-A2 run, because the helicopters proved a greater marginal addition to the M1-A2 force. The RCV would have killed many of the targets the helicopters killed, and thus reaped a smaller marginal benefit. The Red helicopters had a relatively greater contribution than with the M1-A2 run, because of the low number of kills of RCVs by the Red ground systems.

The bispectral smoke excursion was again interesting. Two Blue artillery batteries switched from firing ICM to bispectral smoke. The smoke barrage was laid directly on the Red position and there were virtually no engagements through the first ten minutes, as Blue forces were able to move undetected through the open area to surround and overrun the Red position. A few aerial engagements occurred during this period, but that was the extent of combat. At 11 minutes, when Blue forces were within 100 meters of the Red forces, some close-in shots occurred as Blue began to overrun. By 12 minutes, Blue had overrun all Red positions. Blue enjoyed a slight advantage in kills, and overran the Red position with its forces almost intact. The battle was stopped at 13 minutes.

In this BSS vignette, the relative contributions for Blue were virtually unchanged, quite a difference from the case in BDS. The number of kills by Blue was almost the same for each system, while losses were about 80 percent lower. Thus, the relative contributions of the tanks, AFVs, artillery, and helicopters were about the same as in the CAS scenario. This was not the case on the Red side, however. While the number of Red losses with each system was almost the same, the number of kills by Red tanks fell over 90 percent, and helicopter kills were increased about 75 percent. The distribution of Red kills was left quite even, with a few by each system. This is also a change from the previous excursion, when tanks had accounted for 90 percent of the kills. Overall, the LER was improved by 500 percent, as the use of smoke allowed Blue to completely offset the terrain and defilade advantage of Red. The

number of detections and fires for Blue was cut in half, as were the ranges at which the events occurred. Almost all long-range Blue detections and fires were prevented by the smoke. The number of Red detections, fires, and kills was correspondingly decreased by 90 percent, because Red was essentially blinded by the smoke. Ranges were not so severely affected, but because the number of events is so small (generally less than ten), the numbers can not be considered significant.

The progression of the bispectral smoke excursion using the RCV was quite similar to that of the M1-A2. Smoke again proved itself far and away the most significant addition. The LER for this excursion was increased by 200 percent, a smaller increase than in the case of the M1-A2, but still highly significant. The number of Blue detections was decreased by 70 percent, whereas the number of fires fell by 50 percent. The engagement and kill ranges were off by similar amounts, and the number of detections, fires, and kills for Red were all decreased by 90 percent. Figure 66 summarizes the effects of the various excursion conditions on Red and Blue tank kills. Another way to describe the results is through use of force ratios—the ratio of Red systems killed/Red systems originally, divided by the number of Blue systems killed/Blue systems originally. If this number, shown in Fig. 67 for the various excursions, is greater than 1.0, Blue is winning, if less than 1.0, Blue is losing.

Blue Counterattack Long (BCL) began with three reinforced Blue tank companies in assault formation about 3 km west of the Red position (Fig. 61). Two of the attacking Blue companies were deployed to the north of the river, one to the south. Red forces consisted of one reinforced tank company, deployed in defilade in a wooded area. The first casualties occurred three minutes into the battle, when the Blue companies to the south of the river were engaged at a range of 2.5 km. The pace of battle increased significantly at about five minutes, and continued at a high rate through 12 minutes. Blue sustained casualties to both the northern and southern groups, losing about 10 percent of its forces each minute. Blue was unable to gain any ground, with only one vehicle coming within 1.5 km of Red. The battle was stopped at 14 minutes, when the Blue force had been completely destroyed. Red did not suffer a single loss.

The same vignette using RCVs resulted in a somewhat better outcome for Blue. The first Blue casualty occurred at two minutes, at a range of about 2.5 km. From four minutes to eight minutes, Blue sustained casualties, but at a much lower rate than did M1-A2. Blue also managed to gain some ground, and killed one Red unit. By 11 minutes, Blue forces were able to penetrate to within 1 km of the Red position. At this point there were still few Red losses. At 14 minutes, most of the Blue force was within one km of the Red position and was beginning to overrun. Through minutes 15 and 16, Blue overran the Red position, killing several Red vehicles in the process. Battle was stopped as soon as Blue overran. In the attack Blue sustained 16 casualties, and Red lost five.

In a special excursion, we made a set of BCL runs using bispectral smoke fired by two Blue artillery batteries. The original scenario, fought with the M1-A2 vs. Adv Red MBT combination, was a disaster, with Blue losing over 90 percent of its forces, killing almost no enemy systems, and gaining no ground. With BS smoke, however, Blue forces were able to destroy the Red position, with an LER of .412, almost 70 times better than in the original vignette. Thus, the addition of BS smoke reversed the course of battle, making a successful mission out of an untenable one.
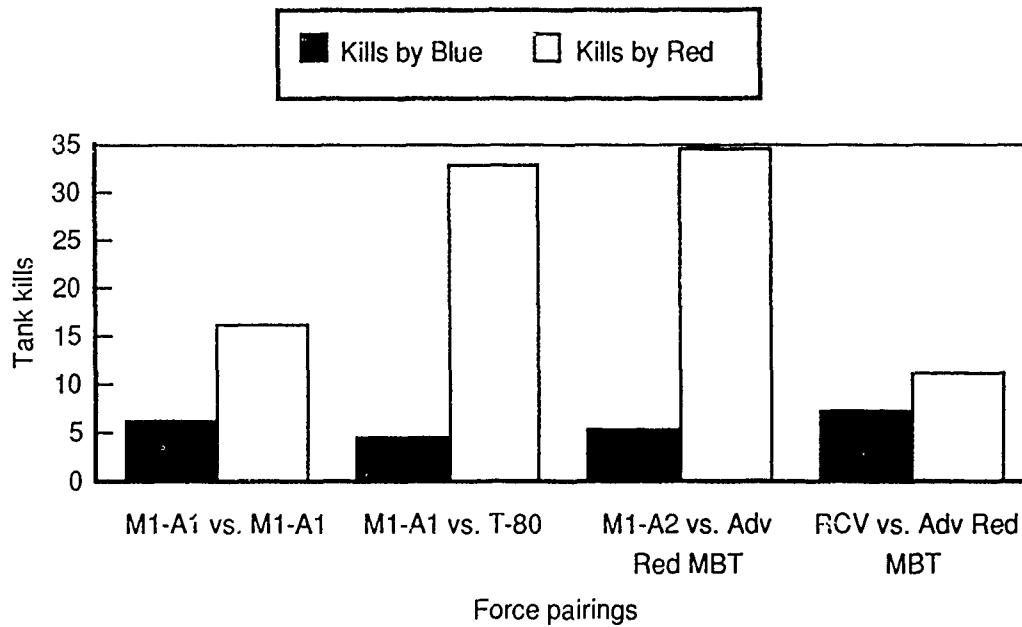
Fig. 66—Red and Blue tank kills in Blue counterattack scenario
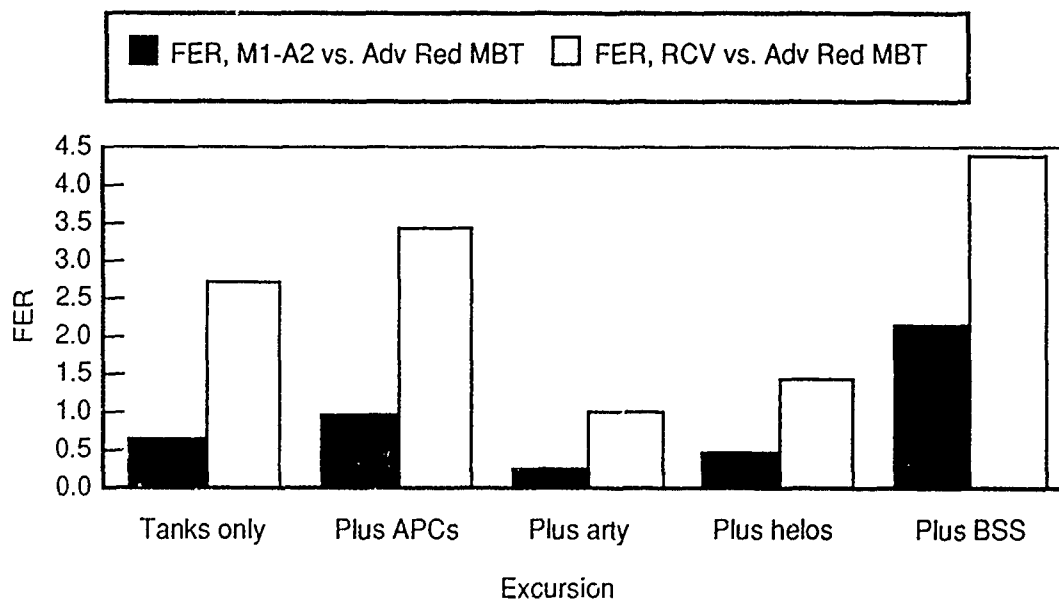
Fig. 67—Red/Blue force exchange ratio for BCS scenario

In the *Meeting Engagement* vignette, two reinforced Blue tank companies ran into two reinforced Red tank companies and engaged along two axes. On both sides, the two companies were moving in parallel, about 2 km apart (see Fig. 63). Blue and Red forces (M1-A2 vs. Adv Red MBT) approached each other on an east-west course. Battle began immediately, with initial engagements between the southern Blue company and the northern Red company, at ranges of about 2 km. Two minutes into the vignette, the Red southern company began to engage the Blue southern company. To this point, the Blue northern company was protected by terrain cover and had not entered the battle area. The pace of battle was quite high, with Blue losing about 10 percent of its forces each minute. The battle continued at this pace from three to seven minutes. At five minutes, the Blue northern company came into the engagement, diverting fire from the southern company, which had largely been destroyed. Losses on the Red side were more evenly distributed, with both the northern and southern forces retaining significant portions of their original force. By eight minutes, the northern Blue company was wiped out as well, and the vignette was ended. The M1-A2 did not fare well in this engagement, losing all of its forces while destroying only about half of the Red force. Detection, engagement, and kill ranges were quite short for both sides.

A meeting engagement excursion with the RCV was quite similar in terms of the course and pace of battle, but led to a very different result, as shown in Fig. 68. With its vastly superior armor, faster firing rate, and more powerful gun, the RCV was able to destroy the entire Red force while losing only about a third of its own forces. Both the northern and southern companies were able to remain effective fighting units throughout the vignette. Detection, engagement, and kill ranges were again under 2 km, a result of the short-range terrain in which the vignette was played.

Hypervelocity Missile Excursions. We made a set of special runs in which hypervelocity missiles (HVMs) were mounted on existing AFVs in the original Blue Defense Short vignette, as well as in each of the BDS excursions. In all, a company of 14 HVM-carrying AFVs was substituted on the Blue side. The results, summarized in Fig. 69, were inconsistent. In the FASCAM and helicopter excursions, Red/Blue LER declined when the HVM vehicles were added. In the artillery and bispectral smoke runs, LER increased. This would imply that the HVM vehicles did not provide a marginal advantage or loss, which might be expected in a short-range vignette. It is important to note, however, that the differences in performance were quite small, typically less than one additional vehicle lost in four of the five excursions. Thus, the variance in results can probably be considered insignificant.

Conclusions

It is apparent that the two-man RCV's observed superiority to current tank designs in the JANUS simulations was due to large advantages in armor and weapon characteristics. In the pure tank force meeting engagement, the RCV achieved a loss exchange ratio over three times better than the improved Blue MBT configuration, and almost three times better than a projected advanced Red tank. In the defense scenarios, the RCV's advantage grows to a factor of 15. In the offense (counterattack) vignettes, the RCV demonstrates over a four-to-one advantage in loss exchange. In particular, the RCV achieved a winning force exchange ratio in the short-range counterattack vignette with only a four-to-one initial force ratio.
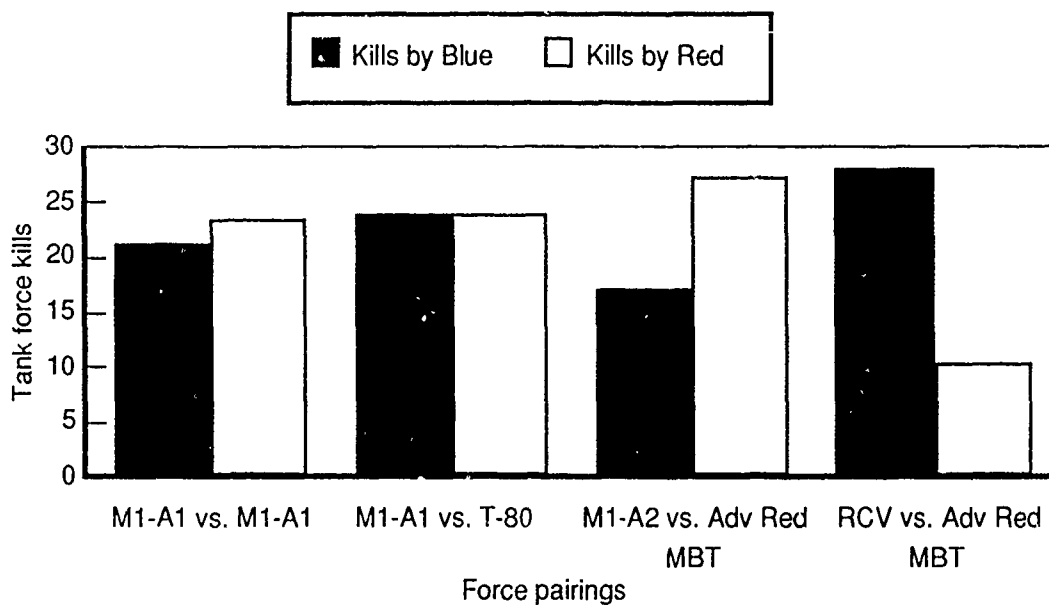
Fig. 68—Tank force kills in meeting engagement scenario
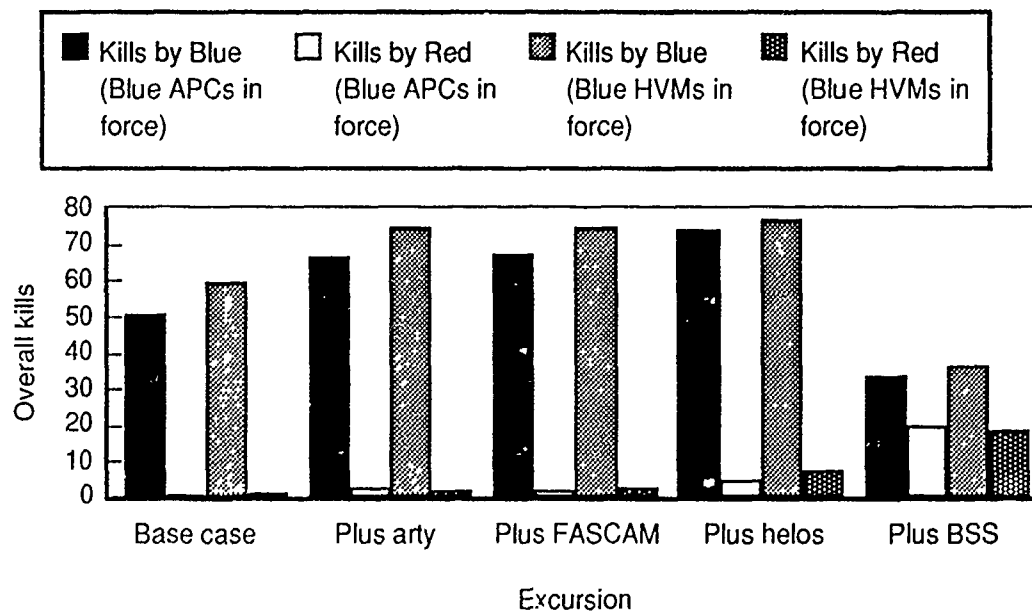
Fig. 69—Overall kills in Blue defense short range scenario with HVMs

These dominating results appear to be due primarily to the frontal armor protection, improved flank projection, and greater firepower and firing rate. Sensor capabilities, size, and signature were held constant for the two vehicles.

The various vignettes by nature stressed different characteristics of the tanks. The Blue defense in short-range terrain (BDS) put a stress on frontal armor, as virtually all shots were from that aspect. A second key factor was firing rate, because multiple targets were engaged in rapid succession. In the BDL vignette, overall armor protection was most important. The Blue counterattack (BCS) primarily stressed sensors, because Blue had difficulty finding the Red forces. Overall armor protection was tested as well, as Blue was engaged from multiple directions. The meeting engagement (ME) stressed firing rate and all-aspect armor protection. In that scenario, the two forces stumbled into each other and engaged in a fire fight.

By looking at system and scenario characteristics together, we can arrive at some conclusions about performance. BDS and BCS make a good comparison analysis, because BDS stresses frontal armor, with firing rate of secondary importance, whereas BCS stresses sensor performance, with armor secondary. The RCV is vastly superior in frontal armor and somewhat superior in firing rate, but has no sensor advantage over the M1-A2. Thus we expected the RCV performance advantage over the M1-A2 to be much more marked in BDS than in BCS. The results confirmed this. The RCV LER was over 20 times higher than the M1-A2 LER in BDS, whereas it was only four times higher in BCS.

A second example is found in comparing BDS and BDL results. The difference here is that the RCV is radically superior to the M1-A2 in frontal armor, but only marginally better in side armor. Thus, the RCV should do relatively better in BDS, with its preponderance of head-on shots, than in BDL, where the shots were mixed. Here again, the results bear out the assumptions, although not as strongly as with BCS.

Our expectations were not borne out when comparing BCS and ME results. Because ME stresses firing rate, while BCS stresses sensors, we expected that the RCV should do relatively better in ME. This advantage did not emerge. The results with the two vehicles were roughly similar, with the RCV doing about four times as well as the BT2, indicating that the rate of fire may not be the primary factor in the vignette.

We did not test any of the three-man RCV designs in our simulation studies. Presumably, the only differences would be larger frontal and flank cross-sectional areas, and slightly higher Pk levels. The three-man RCV may compensate for these shortcomings by having larger search sectors compared to the two-man version.

RISE ANALYSES

We supplemented the JANUS simulation with the RISE (RAND Integrated Simulation Environment) system. We found JANUS to be effective for modeling behaviors (movement, sensing, firing) in a pre-set engagement sequence. The RISE simulation environment adds the capability to adapt engagement behaviors as the scenario unfolds, simulating the functions of onboard AI modules. Our RISE simulations have resulted in programmed behaviors for movement planning, communications management, situation assessment, and engagement planning. The simulation has also been used to a limited extent for exploring user in-

terface configurations. RISE has a variety of components, mirroring some of the complexity and level of integration needed for the onboard AI modules.

Figure 70 shows the basic RISE architecture, centered around an object system written in Portable Standard Lisp. Each scenario object—tanks, aircraft, artillery, even roads and bridges—is represented by an object. RISE supports interfaces between the resulting object-oriented simulation and (1) databases holding terrain models, scenario plans, and history files, (2) graphic devices, (3) networks to other processors, and (4) special purpose routines for calculation of LOS, sensor equations, and other analytic functions. The primary outputs of RISE are preliminary sets of rules for the various AI modules and estimates of system parameters—processing loads, storage requirements, and network bandwidths. Many of these estimates were used in our electronics configuration analysis in Sec. III.

User Interface

We explored alternative screen characteristics of a menu-driven interface implemented with RISE. The user can specify the geographic region, terrain detail, and enemy and friendly situation overlays. Inputs can be made by keyboard or mouse. The simulation can be interrupted at any time to change actions, parameters, rules, or scenario characteristics. For some functions in the operational systems, mission-specific menu systems such as this will be necessary. The actions taken might be screen decluttering, setting screen characteristics, and checking diagnostic indicators.

Plan Language

In our work with RISE, we developed a prototype plan language that supports much of the aiding and automation offered to the crew. This is a formal, Lisp-based language for
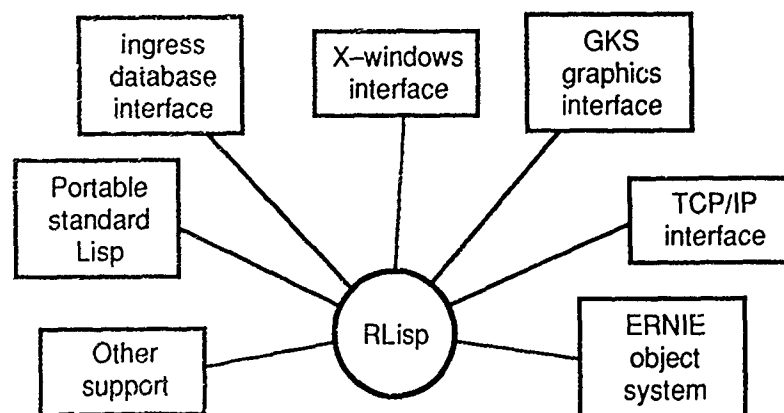
Fig. 70—RISE architecture

temporal control of the simulation entities. The language declares objects, specifies their relationships, supports planning processes, and orchestrates object temporal behaviors during a simulation.

The types of relationships supported by the language are "part of," "commanding," "attached to," "near to," and "in communication network with." These relations are much more general than class-type object inheritance normally found with object-oriented languages. They allow the program to quickly infer many conditions and constraints important to the simulation.

Planning operations are accomplished by traversal of a goal tree. The goals (e.g., movement to a position, destroying enemy forces, replenishing supplies) are organized in an and/or structure corresponding to multiple alternatives (or nodes) and required achievements (and nodes). The system expands this tree successively, determining and testing subgoals against resources and constraints. The approach allows the system to operate dynamically, replanning whenever a subgoal fails or essential conditions change. Planning routines have been implemented for on-road and off-road path determination, deployment planning (for ambush or cover), and engagement sequences. The on-road and off-road planning generally takes a second or two with a Sun 3/60 processor, while more complex deployment planning can take 30 seconds or so.

The basic structure for engagement planning is shown in Fig. 71. Inputs from sensing, communication, and control devices are all placed in the main database, supplementing the current track files and vehicle status data. These are then used to update constructs such as support (neighboring friendly vehicles able to coordinate), readiness (own vehicle capabilities), opportunity (probability of kill weighted across targets), and danger (probability of being detected and killed). These and other intermediate constructs are inputs for decisions on specific actions. Examples of the rules used to implement these functions are given in App. A.

Exploratory versions of these aiding and automation systems have been written in Lisp and C. Operational versions will presumably have to be coded in ADA, which currently has limited capabilities for expert systems programming, graphics interfacing, and parallel processing. Over the next few years, we expect the ADA language to become much more capable in these areas, especially as vetronics applications become more mature.[1]

Example Scenario

Figure 72 was shot directly from the screen during one of our RISE simulation runs. The terrain area is a 6 × 6 km region near Mellrichstadt, Germany, at 50 meter resolution. Two Blue RCVs are in a defensive position on the side of a hill, and six Red vehicles (tanks, BMPs, and radars) move down the river valley. The Blue and Red vehicles plan their movements using a set of off-road and on-road search routines. They also communicate with other vehicles, update their situation estimates, prioritize targets, and plan engagement actions (wait, fire, shoot smoke, run for cover).

---

[1]Philip L. Bolte, "Vetronics: What It's All About," *International Defense Review*, Armour Supplement, Vol. 7, 1987, pp. 13–17.

Input data **Intermediate constructs** **Actions**

Direct sensing
FLIR
Video
MMW radar
RWR

Communications
Data
Commands
Network

Automatic target recognition
Cueing
Location
Identification

User inputs
Commands
Interpretations

Vehicle status
Mobility
Firepower
Sensors
Crew

Track files
Support
Readiness
Opportunity
Danger
Plan
Time stress
Info value
Emergency

Wait
Sense
Move
Engage
Communicate
Alert
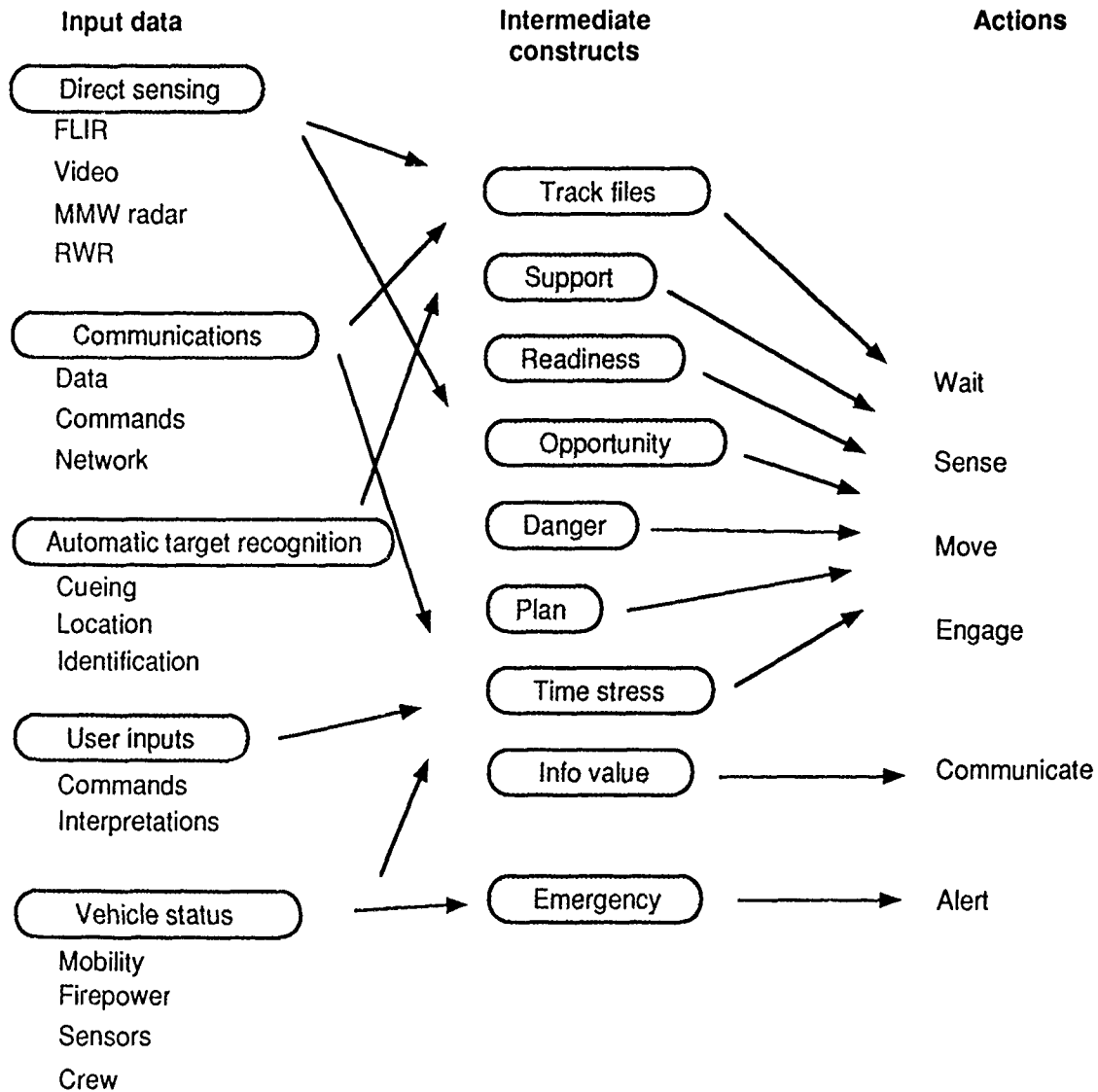
Fig. 71—RISE planning structure

The simulation runs gave us data points for estimating processing loads and storage requirements. For example, we found that while messages required a large number of fields (sender, recipient, routing, type, priority, content, time stamp, etc.), only a few rules (5–10) are needed to decide when and how to transmit the information. Target acquisition and engagement behaviors were found to be much more complex. Hundreds of rules are needed for processing sensor data, updating track files, inputing new target intelligence, checking support from other RCVs, and recommending actions. Even so, only a few seconds will be needed for these functions. Much more processing, including parallel processing and co-rout-

Fig. 72—Example RISE screen image

ing capabilities, are needed if ATR or projection-based planning are used. As described in App. A, around 6 MIPS of processing power and 10–15 Mbytes of memory are needed if ATR is not used. This should result in response times typically less than a second, with roughly linear time decreases if computational power is increased. Estimates of processing loads for the other modules are also listed in App. A.

VII. CONCLUSIONS

In this report, we have pursued several avenues for dramatic change in light and heavy armored vehicles over the next five to ten years. The focus of the work has been on achieving reduced crew designs that are smaller, more maneuverable, more lethal, and harder to hit than their conventional counterparts. We found that it should be possible to use existing and soon available technology to achieve dramatic improvements in close combat system effectiveness. We concentrated on MBT design, but also studied options for light vehicles such as the Bradley and LAV.

We first found that armor protection must be improved substantially over that of the M1-A1 to defeat projected Soviet CE and KE threats. The primary goal here is crew protection, with secondary priorities of the mobility and weapon systems. Placement of the crew in front, surrounded by space-efficient and mass-efficient armors, was determined to be the most effective design option. The turret then provides partial top attack protection. The massive frontal armor also results in adequate frontal arc protection for the electronics, ammunition, and engine. Our armor models showed the front crew/rear engine design to be substantially lighter than the equivalently protected front engine/central crew design.

In our work, we generated vulnerability data using an efficient but nonstandard program. Further work would require corroborating runs of GIFT and VAST programs for at least two of the configurations. These data could then be used directly in JANUS and in calibrating our in-house vulnerability model.

The utility and feasibility of active protection systems should be considered for far future systems. Active armor systems typically use a set of low-power sensing devices to detect incoming missiles or rounds, and then launch and detonate explosives in their path. Unfortunately, these active protection systems have not progressed beyond exploratory component testing, and it would be difficult to extend a utility analysis much beyond a parametric examination.

We reviewed a wide range of weapon systems for MBTs and light armored vehicles: conventional solid propellent guns and autoloaders, liquid propellent guns, electromagnetic guns, hypervelocity missiles, and other missile options. We noted that the weapon must be upgunned from current technology, from roughly 9 MJ energy to 18–20 MJ to defeat projected Soviet armor levels. In the near term, this indicates a large SP gun with two-piece ammunition and autoloader. This decision is by default, because the other technologies are too early in development. Liquid propellent guns have great potential for improvements in bulk and vulnerability compared to SP guns, but have many development hurdles to overcome. Electromagnetic guns seem to be even farther off, due to very large energy storage and conversion requirements. The CAP gun also presents several areas of high technological risk, and should be considered only for far-term applications. Missile systems (particularly HVMs), finally, have been shown to have adequate penetration, but are somewhat bulky and vulnerable. An SP or LP gun can carry many more rounds in the same space. We consider use of the HVM system in our light vehicles, operating farther back from the engagement area than the MBTs.

Propulsion offers even more choices to the designer. We need at least a level of mobility equivalent to the M1-A1, but with considerably lower fuel consumption levels. One-and-a-half or preferably two battle-days of fuel should be achievable. A rear engine system, with an integrated AIPS turbine or diesel configuration, appears most appropriate to accomplish this for the near term. Electric transmission, used in locomotives and large earth movers, is not yet mature enough in this load range. Articulated chassis vehicles, in which crew and weapons are in connected, separate tracked modules, each with its own propulsion, similarly appear to be too early in development, and in fact have seen little recent attention.

Sophisticated sensing devices will be essential on the future battlefield. Direct, out-the-hatch viewing will have to be minimized because of the threat of laser blinding, microwave beam energy, artillery fragments, and small-arms fire. We concluded that for all-weather operation, the operators require a combination of day TV, 8–12 micron FLIR, laser rangefinding, acoustic microphones, and (optionally) MMW radar. Except for the chassis-mounted MMW radar, these would all be mounted on a pair of telescopic masts rising from the turret. Chassis-mounted LLLTVs would provide backup in case the masts are destroyed. The chassis would have radar and laser warning receivers positioned on the corners. Farther in the future, the sensor suite may be augmented by laser radars and 3–5 micron focal plane array FLIRs.

For the far term, more information needs to be gained about sizing, performance, power requirements, cost, and technological risk for each of the key sensing options—SAIRS FLIR, 3–5 micron PtSi FLIR, CO_2 laser radar, FPA MMW radar (possibly with pulse compression), and integrated acoustic/vibration/magnetic sensing. Choice of the sensor suite, of course, depends strongly on the weapon system range and control mechanism.

There will be an increasing amount of image processing in these future systems, beginning with simple image enhancements and target cueing algorithms. POSNAV and JTIDS systems will relay target and friendly vehicle positions to neighboring vehicles. Automatic target recognition should expand to include identification, prioritization, tracking, and possibly automated target engagement. ATR itself seems to be going in three main directions—classical pattern recognition, rule-based AI reasoning, and neural nets. Presumably some combination of these will eventually be used in a massively parallel machine for detecting, tracking, and engaging ground targets against clutter.

Once the vehicles in a unit are connected by a data-link network (JTIDS or some other), we can assume that coordinated tactics will be relied on for sensing, maneuver, IFF, and firing. Important examples will be (1) multistatic sensing, in which a stand-off emitter paints the battlefield and sends registration and timing signals to the friendly vehicles, which receive and interpret the reflected signals, (2) blinking, where different vehicles emit and sense at coordinated, staggered intervals (avoiding home-on-emission missiles), and (3) remote firing, in which one vehicle can sense threats and then order another vehicle, possibly shrouded in smoke, to fire. The logical extension of this capability is application to supervisory controlled robotic vehicles.

Our basic sensor package has the sensors and most of their associated scanning electronics in the telescopic mast pods. Further research is needed to determine the implications of placing only the sensor optics in the external head and passing the resulting images by coherent fiber optic cable to in-chassis detectors (which will require determination of transmis-

sion losses at each frequency resulting from the fiber bundles and connectors/splitters). Design implications will center around image quality vs. reduced sensor cross-section, reduced vulnerability, and more responsive stabilization.

Near-term displays and controls for both the MBT and light armored vehicle designs center around banks of color CRTs (much like the glass cockpits of current aircraft), plasma flat panel displays, sidestick controllers, and programmable touchpads. Voice recognition and synthesis should be used in many situations.

We see helmet-mounted displays as ideal candidates for the far-term vehicles. New versions are coming out almost monthly for aircraft and helicopters. Recent prototypes have binocular vision, color imaging, multiple fields of view, and more accurate pointing and lighter weight than previous ones. Associated virtual touchpads, force feedback sticks, voice input devices, and three-dimensional displays (for horizontal terrain display) are in intense development. Also of interest is the rapid development of high-resolution color flat panel displays. Eventually, we should have display of non-optical sensor images through use of pseudocolor; for example, color could code for depth in a FLIR display. Most of these concepts are visionary at this point, but the possibilities should be considered in a far-term system.

Now that RPVs are again gaining favor, we need to consider use of small stowable ground and air vehicles in our designs. One possibility is to use a small airborne RPV for surveillance. A quiet electric motor craft would be tethered by a power and data line to the armored vehicle to provide a valuable overwatch function. Similarly, ground perimeter security robots can be controlled in an automated or supervisory mode. Some of the same techniques may also be used for limited driving of the manned vehicle, although problems arise with obstacle avoidance, planning, and continuous control.

Most of the AI modules recommended for the reduced crew vehicles use traditional rule-based reasoning augmented by search routines and quantitative algorithms. Further work will be needed to incorporate some of the more aggressive technologies in these programs—neural nets, concurrent projection-based planning, temporal logic, probability calculi, and rigorous information value analyses. All are in developmental stages, and only a few may be appropriate to the types of planning and situation assessment on the RCVs. Nevertheless, the techniques offer possibilities of rapid and powerful decision aiding.

A set of fiber optic data buses and wire power networks (at low and high voltage) will connect the many electronic and electrical components, drawing on the vetronics standards now being developed.

Our designs have not directly addressed the problems of extended engagements, in which crews may have to fight for days at a time. Attention needs to be given to scenarios in which crews may be rotated, 24-hour watch is maintained, and sleep, rationing, and hygiene requirements are met.

In a similar vein, there should be continued exploration of various hatch designs, including those that give full KE protection to the crew and turret ring. None of the designs developed thus far is completely satisfactory.

We have had moderate success modeling the technological and tactical aspects of light and heavy RCVs using our in-house simulation environments—JANUS and RISE. We concentrated our work on the two-man tank, and need to extend the analysis to three-man designs and the Bradley and LAV designs. Further work will require additions to the JANUS routines using the much more detailed CAGIS (Cartographic Analysis and Geographic

Information System) model developed at RAND. This system allows the analyst to examine each simulation step in detail, looking at a small subset of the vehicles. CAGIS provides special models for sensing, mobility, and firing. The work should also move to a high-fidelity environment at some time, such as that provided by SIMNET. SIMNET provides modeling of combined arms operations, some maintenance and repair activities, and simulation of command and control functions. Through special terminals, SIMNET has human and automated opponents, as well as extensive postprocessing capabilities, as described in App. B. Interface with this system would require substantial reprogramming of our RISE and CAGIS code.

Beyond the technology questions themselves, there are larger issues. For example, how do these advanced armor systems fit into future Army warfighting doctrine? How can they contribute to conventional weapons improvement programs? What impact will they have on conventional arms reduction agreements? What are the costs and risks associated with their integration with the whole range of Army systems—from space platforms to smart mines? These questions should be answered though a process of design, simulation, and analysis.

The larger issues stem from the fact that individual conventional weapons systems can no longer be considered in isolation. The battlefield is becoming increasingly fluid, with intelligence being gathered at disparate sites, decisions made at every level of the command hierarchy, and actions taken in close coordination. Information, for example, is gathered by satellites, high-flying aircraft, RPVs, ground vehicles, troops, and emplaced sensors. Coordinated responses are then orchestrated using electronic warfare units, artillery, helicopters, armor, engineering, and any of a wide variety of other units. Sometimes the decisions are made by high-level, centralized command centers and sometimes the battlefield is noncontiguous, with decisionmaking distributed over disconnected lower-echelon commanders. In either case, adding new vehicles or new technologies can have unforeseen impacts on mobility, firepower, vulnerability, or other unit performance measures. Such changes may also result in completely new tactics and doctrine, and they may have hidden costs for staffing, maintenance, or transportation.

These questions should be answered (at least to a preliminary degree) through use of simulations and analyses that span the range from Echelons above Corps (EAC) to individual vehicles and subsystems. Simulations include such Army systems as VIC, JANUS, and SIMNET, and RAND systems such as TAC-SAGE, S-LAND, CAGIS, and RISE. Many of these simulations are described in App. B. They range from traditional FORTRAN models to highly interactive object-oriented simulations. The types of questions that should be answered include the following:

- How should tasks and command responsibilities be allocated among the different systems? For example, should air defense be centralized or distributed?
- How should information (contacts, commands, status data, queries, etc.) be passed among the units? Should the organizations be loosely coupled or tightly connected?
- How robust are the units to new threats, upgrades in armor and weapons, special tactics, difficult terrain, bad weather, and lack of support?
- What are the incremental costs and benefits associated with introduction of new systems into the conventional weapons force?

152

- How will post-CFE (conventional armed forces in Europe) scenarios, with their emphasis on force projection rather than forward deployment, affect the use of light and heavy systems?

These questions will require sensitivity analyses, a wide range of scenarios, and extensive testing and analyses. The question on costs and benefits will require careful specification of performance indexes. Life-cycle costs and risks must be estimated. Performance measures may involve simple acquisition and kill probabilities, or they may center around such aggregate indexes as extent of penetration into Central Europe, given a defensive force with a set cost or with a set number of units. This analysis will have to be made at several levels of abstraction (e.g., theater, division, battalion), and over a se' of scenarios. It may require special additional models for mobility and logistics. All of the work will have to be validated with human gaming, analytic studies, and field exercises at the National Training Center, the Warrior Preparation Center, or Red Flag Exercises.

Appendix A

AI MODULES FOR REDUCED CREW
ANTIARMOR VEHICLES

OVERVIEW

This appendix describes each of the eight AI modules planned for the reduced crew vehicles. The MBT, Bradley, and LAV versions should each use virtually the same architectures and components. The AI modules cover such critical mission functions as situation assessment, communication management, engagement planning, and fault diagnosis.

The descriptions include input parameters, processing computations and rules, and output actions. They are written in a pseudocode form—one that is easier to read and understand than Lisp, C, or ADA. The individual sections provide estimates of processing loads, and in many cases, example behaviors are given. We will give examples of how certain of these functions were developed and tested using the RISE simulation environment. The appendix concludes with a very rough summary of system support requirements.

NAVIGATION AIDING

This module is primarily a driving and mission planning aid. It receives position and intelligence information from the communication system (SINCGARS or PLRS/JTIDS system), terrain information from the onboard memory store, and plan information from the object database. It should also get stand-alone position and orientation information from a three-axis onboard ring gyro. The input information is characterized as follows:

Own vehicle:
> latitude, longitude (deg:min:sec)
> elevation (meters)
> vehicle orientation (deg)
> sensor, gun angles (deg)
> status (list: damage, fuel, ammunition)
> current plan (list: coordinates, times, activities)

Support (each friendly vehicle):
> latitude, longitude (deg:min:sec)
> elevation (meters)
> orientation (deg)
> current plan (list: coordinates, times, activities)
> status (list: damage, fuel, ammunition)
> communication links: (LOS, non-LOS, jamming)
> activity (moving, stopped, firing)

Threats (each vehicle):
 latitude, longitude (deg:min:sec)
 elevation (meters)
 orientation (deg)
 status (damage)
 activity (stopped, moving, firing)

Autodrive inputs:
 speed (km/hr, duration in seconds)
 turns (deg, time in seconds from start)

The module updates the flat panel map display by creating and moving icons for own and enemy units, and by redrawing paths for planned movements. If a helmet-mounted display is present, the system also senses head orientation. In the terrain database, navigation information is represented as object attributes in the following way:

Unit type (tank-1, APC-3, helicopter-1)
Unit color (Red, Blue)
Unit position (latitude-longitude, elevation)
Unit activity (march, stop, defilade)
Unit orientation (deg)
Unit status (operational, damaged, killed)
Data confidence (probability)
Data time stamp (day:hour:minute)

Using this information, the navigation aiding module performs several key functions. It generates and displays LOS fans for own and known enemy units, and uses them to define danger regions. It provides recommendations for movement and deployment. It also executes automated driving in emergencies. Each of these is described in more detail below.

- LOS fans and danger regions are fairly straightforward. Line-of-sight fans are calculated and displayed for each enemy and friendly unit. The extreme range of each fan is calculated as a function of sensor type, time of day, environmental conditions, and target activity. The extreme range can be selected for detection, identification, or recognition. Danger regions are then specified as those areas that the enemy can both identify and engage. They can be shown as highlighted regions on the map display, and if called for, on the perspective display.
- The route planning routine is called whenever there is a need for movement, usually because of new objectives, loss of support, or new threats. In effect, the routine searches for the best (least distance, least elevation gain, least exposure) path from the current position to the goal. As currently implemented in the RISE simulation environment, the system accesses the appropriate map area, checks for threats on adjacent map segments, and generates on-road or off-road paths expanding out from the current position. The paths are evaluated and the best one displayed to the operator, along with annotations of estimated arrival time and level of expo-

sure. If the recommendation is rejected by the operator, the system displays the next ranking alternative or accepts direct input from the operator. During actual movement, the system will prompt the operator with directions to follow.

- Deployment aid is a special set of rules used to decide on defensive positions and intervehicle coordination. The system accepts operator inputs (mouse inputs in our simulation, control stick or touch-screen inputs in the operational system) indicating the general area to move to and specific regions to defensively cover. The system then searches for the position exhibiting best line-of-sight coverage while satisfying constraints for spacing and communication links between friendly vehicles. Again, the recommended deployments are displayed to the operators on the map display. Implementation of the function with the RISE environment was found to be straightforward, using some several hundred lines of code and 2–3 Mbytes of working memory.

- Automatic driving. We assume the system will not be able to take over on-road or off-road driving, as this entails complex reasoning about the visual scene and special capabilities for obstacle avoidance. Instead the system will perform emergency automated driving over a previously learned route. The operator will drive the vehicle to a cover or alternate firing position, and the system will record the throttle, steering, and braking. The system will then be able to "play back" the sequence without human intervention if an emergency arises.

The outputs for the navigation aiding module are:

To map display: overlay plans on terrain map and show movement commands, exposure areas, coverage, and deployments.

To command and control module: changes in plans to be communicated to neighboring units.

To control bus: throttle, brake, transmission, suspension commands during automated driving.

In support of the navigation aiding function, we will need large amounts of digital terrain map storage. Each vehicle will need roughly 100 km × 300 km of terrain at a minimum of 50-meter (preferably 12.5-meter) resolution. Each point will have associated elevation, cover, and mobility. The database will have features or objects representing roads, railroad tracks, built-up areas, bridges, and other important entities. The objects will have such attributes as throughput, traction, obstructions, and width of access. The route plans themselves will be represented as lists of line segments. Each segment will be annotated by speed, actions, and constraints. Currently, the RISE simulation supports input of route segments using a mouse, and then searches for an appropriate detailed route. Mass storage should be on the order of 50 Mbytes disk and 5 Mbytes RAM, while processing for planning activities should require a minimum of 4 MIPS.

All of the above functions should be achievable for a near-term (4–5-year) system. Farther in the future (8–10 years), we might expect navigation overlays on three-dimensional

map projections. The routes and deployments would then be generated using highly efficient variations of the search algorithms. Even with this procedure, the minimum processing requirements will at least double, and support of three-dimensional projections will require a dedicated graphics engine, such as the Chromatics 1500, capable of handling 500,000 vectors/second.

SITUATION REPORT AND ASSESSMENT (SR&A)

This module examines the current and past data in the track files, and makes inferences about enemy position, tactics, and knowledge (what enemy units know about the reduced crew vehicles). The SR&A module also makes inferences about friendly support and communication network status. It does not operate directly on raw sensor data or on newly received communications. These direct information inputs are incorporated into the database by other modules, as described in subsequent subsections. The SR&A module simply operates on the database information, making changes, informing the operator, and communicating new data to neighboring vehicles. The inputs to the module are:

Track files (for each friendly and enemy vehicle):
     position
     type
     activity (speed, direction of movement, behaviors)
     status (operational, damaged, dead)
     side (Red, Blue, unknown)
     data confidence (probability)
     sensors used to detect, recognize, identify
     area (road, field, forest)
     derived data—range, LOS, opportunity, danger
     vehicle plan

Environmental conditions:
     wind, fog, rain, snow
     day/night
     smoke

Enemy tactics:
     force level
     movement tactics
     impending actions

Most of the SR&A behaviors are expressed as rules or schemas. Rules are if-then constructs, organized into rulesets corresponding to specific situational conditions. Some examples of rules are:

If target(s) moving along road, assume
     self not detected,

other threats are in group,
and threats will continue movement along road.

If target(s) move off road, shooting smoke and running for cover, assume
own presence detected, and
targets will stop and set up defilade.

If broadcast communications from a stationary site behind the forces, assume
a command center is stopped and active, and
other forces are in area.

Schemas are more complex representational forms similar to frames. Schemas have time-tagged actions and variables that can be fitted to the immediate conditions. Schemas are used, for example, to describe the coordinated actions involved in a bounding overwatch maneuver or a phased withdrawal. Schemas would specify vehicle speeds, communication times, emergency actions, and other behaviors.

The outputs of the SA&R module are:

To displays: alert operator to immediate danger or opportunity,
show expected actions, show changes in
situation—support, actions, etc.

To database: make entries about inferred enemy strength, position,
tactics, and knowledge (intelligence about Blue).

To command and control: send messages to neighboring units when
major change in situation assessment.

The Situation Assessment and Report module will in fact be the repository of the track files, the comprehensive database used to keep track of all force data. This database should be a minimum of 4 Mbytes to maintain histories about all contacts during an engagement.

In the near term, a set of 100–200 rules organized into five to ten rulesets should be sufficient for responding to the key situations expected. By programming a subset of these rules in RISE, we found that only a minor amount of processing power (.5 –.7 MIPS), but a large amount of storage (5 Mbytes) should be required.

In the far term, complex coordinated scenarios, in which the RCV interacts with aircraft, artillery, and air defense units, will have to be orchestrated with schemas. The more complex scenarios should demand an order of magnitude more processing power than the rulesets, but the higher level of inference should only be necessary for command centers, not for individual vehicles.

COMMAND AND CONTROL (C^2)

This module is responsible for all communication behaviors. It handles generation, transmission, receipt, and interpretation of messages. The C^2 module also maintains a

communication table enumerating the most recent status of each point-to-point communication link, and updates the table whenever a communication is received.

The types of communication include data, data queries, acknowledgments, and commands. Data may be critical situation alerts, concept of operation, maintenance/supply status, heading reference, IFF signals, or enemy disposition. Data queries of a friendly unit may involve questions about any of these. Commands, on the other hand, are specific orders to perform some action—sense, move, engage, or wait.

The inputs to the command and control module are the following:

In-messages
Out-message requests
Track file data:
      threat status
      danger
      activity
      recipient knowledge
      plan
      communication system status data

The communication process itself is fairly standardized. Messages typically have the following format:

Sender
Receiver
Routing (intermediate hops on way to recipient)
Type (data, request, command, acknowledgment)
Content
Priority
Time stamp
Link status (open, jammed, blocked)

Prior to sending a message, the C^2 module determines the value of information for the transmission. This computation weighs the usefulness of the information to the recipient against the costs of transmission. The sender keeps a record (in the track file) of what information has been sent to whom. A data item is valuable depending on its type, its recency, and its impact on the recipient (e.g., a threat contact near the recipient is more important than one far away). The transmission cost depends on the danger and channel capacity. A message should be sent only if the information value is a net positive. In the near term, simple surrogate rules will be used in place of a full information value analysis. For example,

Send target detection message only if danger < .4, emergency
    not present, and target is in range of recipient.

A full information value analysis would estimate the change in expected value to the recipient as a result of the message. This requires inferences about the recipient's knowledge, status, and plans.

In several ways, the system will attempt to ensure LPI (low probability of intercept). Transmission power will be reduced to that necessary to reach the recipient. Antenna direction and shaping should minimize energy in the direction of the enemy. Transmission timing takes advantage of LOS changes.

In the near term, only a SINCGARS communication capability may be present. This single-channel system will result in an inability to transmit video or other high-bandwidth information. Slow scan TV may be possible using a data compression system. JTIDS/PLRS (also known as enhanced PLRS or E-PLRS or PJH) should dramatically increase bandwidth and security when it becomes available.

Outputs of the module are the following:

To system control: display in-messages
   display generated out-messages
   indicate when to send message
   indicate that message has been sent
   display communication link status.

To track files:
   incorporate information from in-messages
   update communication link status entries.

The processing load of the command and control module should be minimal to moderate. The main burden will be the information value analysis, which, if done simply according to message type and danger, will require only about 1–2 MIPS. If information value analysis takes into account inferences about recipient knowledge, detection danger, and channel usage, a minimum of 2–4 MIPS and 2–3 Mbytes of storage will be needed.

TARGET ACQUISITION AND ENGAGEMENT (TA&E)

The TA&E module is the most complex of the eight in the RCV. It processes the raw sensor data, updates track files, inputs new target intelligence, checks support fro other RCVs, and recommends actions according to the circumstances and mission plan. The inputs to the module are:

Sensor contacts:
   Raw sensor scans—TV, FLIR, MMW, laser scanner
   Radar warning system alerts
   Data by sensor type:
     threat location
     range
     identification

cues (MTI, muzzle flash, missile launch)
orientation
emissions

Track file:
History of target positions
Threat identification (from communications or previous sensings):
tactics, plans
knowledge

Own support data:
status—activity, damage, supplies
plans

Environmental conditions:
Smoke
Fog
Dust
Day/night
NBC

Operator inputs:
Target designations
Sensor commands
Display commands
Action choices

The specific inputs to the sensor processing module include threat shape, doppler signature, glint, size, range, contrast, resolution, composition indications, and hot spot configuration.

The target acquisition and engagement module works at several levels. The first is processing immediate sensor returns. Images from the video, IR, MMW, or laser scanner systems are placed in a common coordinate system. Each contact is associated with a given track file, which may turn out to be a true target or a ghost image. Further contacts add confidence to the position, type, or activity propositions about the threat. The confidence changes are made according to a belief and disbelief representation. Intelligence messages are also added to the track file information by the command and control module. A sample track file entry might be:

Contact 004
Type: helicopter (Hind)
Moving: yes
Position (latitude-longitude, elevation)
Activity: pop-up
RCV detection: no

Confidence: .70
Recency: 010
Sensors used: visual wide, FLIR wide
Messages: (time 012, recipient B1)

In the first level, the TA&E module moves through the applicable sensors to add information about likely threats. The system will often detect a target while searching with passive, wide FOV sensors such as the LLLTV and FLIR. Identification may then result from a change in magnification. If this fails, and the target is a likely high-priority threat, the system may call for active sensing—MMW radar if smoke is present; laser radar if conditions are clear and high-resolution information is needed.

At the next level, the TA&E module updates a set of special constructs used for decisionmaking. These constructs, listed below and explored using the RISE environment, are based on the track file data:

- Danger: The likelihood (summed over threats) that the RCV will be discovered.

- Opportunity: The weighted probability of kill across the set of targets. Weighting is by target value.

- Support: The number of RCVs in support range and with open communication links.

- Emergency: The presence of extreme danger, such as being scanned by laser or fired at.

A moving tank sighted at 2000 meters, for example, may result in moderate danger (assuming it has not sighted the RCV) and high opportunity. If the RCV is in defilade, this will not be considered an emergency. All of these intermediate constructs are represented as interval-valued entries. For example, opportunity is the sum of enemy threats in firing range, weighted by Pk and value. Prioritization also results from this information.

When any of the above intermediate constructs change, the next level of processing is called. If an emergency arises, immediate actions—fire, shoot smoke, run—will be initiated. If it is not an emergency, and time is available, the system can either access rulesets, fitting behaviors to the situation, or it may use simulation-based planning to examine multiple options. The simulation-based planning is done by running simulations of the projected enemy and friendly behaviors, and evaluating the outcomes. The recommended action may be an overt response, a change in sensor setting, or just to wait. To perform such lookaheads, the system must have a special object system and it must support coroutines (so that multiple projections can be made and compared). Our work with the RISE simulation environment and a custom object system with coroutines has shown this to be feasible.

Simple rule-based behaviors in response to battle conditions should be relatively effective for the near term and should cover most basic situations. In the far term, full simulations and chess-like analysis should be possible with powerful concurrent processing systems.

These systems will be able to explain the reasoning behind their choices and replan when complications arise during an engagement.

The outputs of the TA&E module are:

To system control (displays/controls):
      raw sensor data on perspective display
      overlays of threat, support icons on map, perspective displays
      overlay of recommended actions on map, perspective display
      summary of situation—danger, opportunity, etc.—on text display
      change mode of control grips, touchpads.

To control bus: sensor control commands
              weapon control commands.

To command and control: data messages of sightings, readiness
                         target negotiation messages
                         fire control, movement, command messages.

The expected processing load for the many TA&E functions should be fairly high:

Updating track files:	0.5 MIPS, 2 Mbytes
Update intermediate constructs:	0.2 MIPS, 0.5 Mbytes
Make engagement plans: rules	0.5 MIPS, 0.3 Mbytes
(far-term) projections	5 MIPS, 8 Mbytes
Approximate total (near term):	1 MIPS, 3 Mbytes
Approximate total (far term):	6 MIPS, 11 Mbytes

A special, optional part of the SR&A module is an automatic target recognition (ATR) system. This system coprocesses data from up to three sensors simultaneously, attempting to detect, recognize, and identify targets. In the near term, some target cueing functions should be possible—alerting the operator to possible targets of military interest, placing the cursor on them, and adjusting the sensor field of view. The more difficult ATR functions— recognition and identification—should be delayed until the more distant future. The far-term processing loads are expressed in BOPS (billions of operations per second):

ATR system cueing: 1–2 BOPS
        recognition: 6–8 BOPS

SECURITY STATUS

This module orchestrates all sensing, alerts, and responses to area intruders near the vehicle. The system uses whatever sensors are available to detect short-range movements or intrusions. During an engagement, of course, no sensors may be available. The main security functions will be exercised when the RCV is in silent watch or the crew asleep. Then the

security status module will use the TV, FLIR, or MMW, setting power, field-of-view, and scan envelope according to the terrain, cover, and expected threats. If the MMW is used, the power must be set low enough to avoid detection by enemy vehicles.

The inputs to this module are:

Sensors:
    raw sensor returns
    environmental conditions

Track files:
    vehicle plan
    terrain map
    expected threats

ATR cueing

Using limited ATR capabilities, the sensor system may determine if contacts are potential threats and whether to train sensors on the threat. The system also decides whether to alert the operator. An example rule might be:

If the MMW radar or FLIR detects a contact of suspicious movement and size, then alert operator, zoom in on threat, and activate displays.

These types of rules can be used to drive the set of sensors currently planned for the RCV. In the more distant future, the system may control a dedicated robotic sentry vehicle.

The outputs of the system are:

To system control (displays):
    raw sensor scans
    alerts
    recommended actions
    control grip mode

To control bus:
    adjust sensors
    ready weapons

The processing load is relatively low for this module, except for the ATR function. The rulesets should require approximately 0.2 MIPS and 0.1 Mbyte, whereas the ATR function may require as much as 0.5–1.0 BOPS.

POWER DISTRIBUTION AND CONDITIONING

This module monitors the immediate and projected power demands for the various vehicle subsystems: turret drive, autoloader, electronics, NBC system, starter motor, and so

forth. It checks battery reserves and determines if APU or main engine activation is needed. It prioritizes demands and recommends actions according to activity importance, danger of APU or main engine emissions, and effects of voltage spikes. If the combat vehicle has regenerative braking from an electric transmission, the power module determines whether to direct the current into the vehicle power bus, the battery, or a resistance pack. The inputs to the module are:

Track files:
vehicle activity
vehicle plan
danger

Power bus:
immediate power usage
electrical system status—battery, APU, main power

In the near term, power distribution will be limited to responses to immediate power demands. Later, when simulation-based planning is instituted, power distribution will be based on projected demands. Also, near-term power networks should all operate at 28 VDC, whereas in the far term, a separate high-voltage turret drive circuit may be added for increased performance.

The outputs of the system are:

To control bus:
power distribution to subsystems
APU activation
main power activation

To system control (status display):
display of power situation
recommendations

Minimal processor load and storage will be needed to support the rule-based behaviors. Simulation-based planning for dynamic power distribution, on the other hand, would require as much as 5 MIPS and 6 Mbytes.

MAINTENANCE AND SUPPLY (M&S) STATUS

The routines in this module check propulsion, weapon, electrical, and electronic system indicators, alerting the operator and the maintenance/supply groups to specific problems. In many ways, the functions are similar to those already in operation in sophisticated automotive diagnostic systems. The module also initiates emergency responses to fire and smoke detections, activating the fire suppression system. The list of inputs is a long one:

Engine, transmission:
    hours
    temperature history
    kilometers at load
    brake wear
    oil levels and usage
    coolant level
    fault indicators—vibration, airflow, fuel usage,
        mixture, shift points, power delivery

Suspension, tracks:
    kilometers at speed
    pad wear
    track tension
    suspension travel
    vehicle height and cant
    fault indicators—electrical self test, hydraulic loss,
        track slippage, track loss, power delivery

Electrical system:
    battery amperage
    alternator output
    APU output
    power waveform or cleanness

Sensors, communication system, processors, mass storage:
    operational hours
    sensor, amplifier, processor temperatures
    power output
    data bus throughput, error rate
    disk failure
    processor failure

Environmental system:
    airflow
    temperature
    humidity
    filter pressure drop
    protective door status

Stores:
    fuel
    oil
    rations
    ammunition (by type)

Emergency indicators:
    smoke
    fire
    NBC alarm
    flooding
    subsystem damage

Maintenance/supply history (from database):
    modules replaced/repaired
    servicing
    replenishment

For maintenance and supply, the module maintains a database of system loads, repair history, and component performance. If attention is required, the system may alert the operator, graphically displaying the problem, or it may generate a message to the support group. The M&S module is typically called when an out-of-threshold condition is sensed, when mission plans change, or when a preset time interval passes.

The processing activities are quite varied. The M&S module checks accumulated time and load against a maintenance schedule. If maintenance is called for, the system checks the mission plan, notifies the operator if a priority threshold is reached, and sends a message to the maintenance group. It checks expendables usage against current levels, determining if they are sufficient for the mission plan. If not, the system again alerts the operator and support group. The module responds to emergency conditions. It shuts down vulnerable subsystems, activates the fire suppression system, and alerts the operators visually and verbally. Finally, it aids in fault diagnosis, showing the fault tree for the failed system and searching for the failure. It may do so automatically or just act as an aid to the operator, depending on the difficulty of the problem and the demands on the crew. Some of the automated functions include calling backups for memory, processor, network, and sensor systems. The full set of outputs for the M&S module are:

To system control (status display):
    diagram system status
    show recommendations

To command and control
    generate messages to maintenance, supply groups
    generate status message to other RCVs

To M&S database:
    enter maintenance, supply, load, performance data

To control bus:
    commands to fire suppression system, subsystem
    deactivation, activation of backup systems

In the near term, the maintenance and supply module will aid in the form of alerting, diagnosis, and communication functions. Later, we can expect automatic fault recovery and reconfiguration of processors, memory stores, electrical buses, and the like.

The processing load for the maintenance and supply functions is minor for aiding and emergency responses (0.2–0.4 MIPS, 2–3 Mbytes), but substantial for the far-term automated fault diagnosis and system reconfiguration operations (5–6 MIPS, 4–5 Mbytes). General Dynamics Land Systems, for example, plans to use a 6-MIP processor for troubleshooting the current M-1.

SYSTEM CONTROL

This module controls the activation of the other modules and acts as an intermediary between them and the user. It formats displays and reconfigures controls (control grips, touchpads) according to the situation. In the more distant future, the system control module will also decide which functions should be automated, how to allocate control between the operator and the automated system, and when to ask for human intervention.

The system control module checks the vehicle activities (movement, search, communication, engagement), observes the operator inputs (menu choices, control actions), and configures the display screens (or helmet-mounted displays) accordingly. Continuous control functions with the displays will normally be entered with the control sticks. Pointing operations may be made using touch-sensitive displays, as long as the accuracy does not have to be better than about 5-mm. Discrete inputs will be made using touchpads and control grip switches.

The inputs to the system control module are:

Navigation aiding module:
    map display:
        updated terrain map with situation display, assumed danger regions
        plan overlays

Situation assessment and report module:
    map display:
        new inferences about danger, opportunity, support, and emergency

Command and control module:
    status display:
        queue of messages
        communication link table

Target acquisition and engagement module:
    map display: threat disposition, plan overlay
    perspective display: threat highlighting, annotating
    status display: action recommendations
    control mode: change display control to sensor control
        to weapon control

Security status module:
    map display: threat location, type
    perspective display: threat highlighting
    status display: action recommendations

Power distribution and conditioning module
    status display: power distribution, recommendations

Maintenance and supply module:
    status display: stores summary, fault diagnosis
        diagrams, recommendations
    map display: supply vehicle positions

Track files:
    target and friendlies: positions, types, status, activities
        own status and activities
    intermediate constructs: opportunity, danger,
        support, emergency

User inputs:
    control grips
    touchpads
    touch-sensitive screens
    voice commands
    head movement (if HMD)

Some sets of display and control configurations will be automatically set by the situation. For example:

Emergency contact (incoming missile, security alert) will result in verbal and visual alerts. There will be highlighted areas on the perspective and map displays of the threat, with the magnification set to 1:1 and the display centered on the threat. The control grips will be set to weapons.

Dual search (both operators scanning for targets). Each will have independent search areas, scanned at 1× or 3× magnification, with target cueing from the ATR system. The touchpads and control sticks will be set for display controls.

Tracking and identification. The magnification will be increased to 10×, with ground stabilization. The threat will be centered on the screen. If necessary, the user will call for freeze frame or multiframe averaging to get a better image.

Maintenance and supply. The system will bring up vehicle status display with voice generation. Touchpads will be set for moving through configuration diagrams or expendables summaries.

The system will also aid in such traditional man-machine interface (MMI) functions as pan, zoom, rotation, highlighting, alerting, and decluttering. Some of these functions may be activated by voice command. The outputs of the module are:

To display screens:
    pan, zoom, freeze, average
    icon overlays
    data suppression
    text summaries
    fault trees
    power networks
    supply histograms

To controls:
    touchpad legends
    control grip functionality
    voice inputs

The processing load for the system control module should be moderate, except for the graphics engines. Rules for control of the MMI should require no more than 2 MIPS and 0.5 Mbytes. The graphics engines should require 12–24 Mbytes of storage for generating and buffering high-resolution images.

In future versions, the module may check user activities, estimate the user load, and take over those functions not handled by the user. For example, during driving operations, the module may direct the command and control module to perform all data communication tasks automatically, and indicate to the user what messages have been sent. The module may use physiological indicators such as response time and correction frequency to decide whether to further unburden the operator. The interface will normally be mixed initiative, with either machine or human making queries or reconfiguring the system. Final override, of course, will always lie with the human operator. Data processing and storage requirements for this system would be at least double that for the near-term system.

ESTIMATED PROCESSING LOADS

Rough estimates of the minimum total processing and storage requirements for the near- and far-term systems are:

Module	Near Term		Far Term	
	Processing	Storage	Processing	Storage
Navigation	4 MIPS	5 Mbytes	8 MIPS	10 Mbytes
Situation report	0.5 MIPS	5 Mbytes	2 MIPS	8–10 Mbytes
C^2	1–2 MIPS	—	3 MIPS	2–3 Mbytes
Target engage-ment	1 MIPS	3 Mbytes	6–10 MIPS	8 Mbytes
Security	0.2 MIPS	—	0.2 MIPS	—
Power distri-bution	0.1 MIPS	0.1 Mbytes	5 MIPS	6 Mbytes
Maint./supp.	0.3 MIPS	2 Mbytes	5 MIPS	4 Mbytes
System control	2 MIPS	0.5 Mbyte	4 MIPS	1 Mbyte
Graphics engines	—	12–24 Mbytes	—	30–60 Mbytes
ATR processing	—	—	5–10 BOPS	—
Total	9–10 MIPS	25–40 Mbytes	33–35 MIPS 5–10 BOPS	60–100 Mbytes

These figures assume a response time of less than a second for most decisions. Increasing the computational power should result in roughly linear decreases in response times.

Appendix B

SIMULATIONS AND SIMULATORS FOR EXPLORING COMBAT VEHICLE DESIGNS

INTRODUCTION

This appendix surveys the many simulations and simulators that have potential for exploring, developing, and refining new, reduced crew armored vehicle designs. *Simulations*, in our context, are computer models that abstract and examine some aspect of vehicle operation. They do not attempt to achieve great fidelity or realism. Instead, they usually examine how the system behaves in an engagement scenario, through the use of mathematical models and computer-graphics. *Simulators*, on the other hand, attempt to reproduce the critical aspects of vehicle operation to human users. They typically use computer-generated imagery and realistic crewspace mock-ups to duplicate the experience of operating the vehicle. *Simulations* are generally used for detailed analysis (system performance characteristics, doctrine, tactics, etc.) whereas *simulators* tend to be used for training and human factors studies. Both analytic simulations and high-fidelity simulators are important to the development of advanced ground weapons platforms.

We will describe below a number of simulations and simulators. We will look at two main types: low-level, vehicle-on-vehicle systems useful for examining detailed vehicle operations, and high-level, abstracted engagement systems designed for exploring tactics and doctrine. No single system appears fully appropriate to our effort, but we will identify those systems that can contribute to our development program. We will note those systems that we have used to this point to explore designs, capabilities, and tactics. We will finish by recommending a set of systems for further analysis and development.

SIMULATIONS

Ground warfare simulations range from detailed vehicle-on-vehicle systems to extremely large-scale theater warfare models (with resolution only to corps or division level). Our armored vehicle work focuses on the design characteristics of the individual vehicle, with higher-level intervehicle coordination and tactics as a secondary concern. Four simulations offer detailed modeling of individual vehicles on high-resolution terrain models—Ground Wars, JANUS, CAGIS, and RISE. The other simulations described in this subsection—VIC, T-SAGE, ConMod, CASTFOREM, Carmonette, Campaign, S-Land—are all at battalion resolution or above.

Ground Wars

This FORTRAN simulation, by AMSAA, is the most detailed of the models surveyed. Ground Wars is an enhancement of the outdated TXM (Tank Exchange Model) simulation. It

extends TXM by allowing 10 on 10 engagements instead of 1 on 1, adds a variety of sensors, and has many special models, such as artillery effects and several kinds of smoke.

The detail modeled by Ground Wars seems impressive. It is supposed to model TV, FLIR, laser ranging, and to a rough approximation, MMW radar. Terrain is modeled statistically instead of from a terrain map, and line-of-sight calculations depend on the position and movement of the forces. Four or five types of terrain are given, with engagements normally beginning at about 5 km range. Smoke is modeled explicitly, with either statistical effects (holes occur in the cloud) or by an atmospheric degradation for the whole cloud. Armor distribution and thickness are modeled, along with weapon effects. Various guns and munitions can be selected. Two types of scenarios are typically run—a hull defilade defense against an offensive unit, and a meeting engagement with both sides in the open.

The FORTRAN program is available on tape. It takes up only 7000 lines of code, but is typically run on a powerful Cyber machine. A 6 on 2 engagement with smoke is supposed to take about two minutes. On a VAX or Sun 4, that might be 20 or 30 minutes (there are large numbers of smoke, line of sight, and armor penetration calculations). There is no graphics display, only a tabular output. Input is somewhat more interactive as the user must define travel paths. The simulation seems best suited to modeling detailed weapon effects.

JANUS

JANUS is an interactive, battalion//brigade-level, two-sided simulation developed by Lawrence Livermore National Laboratories and later refined by TRASANA. The simulation is programmed in FORTRAN and run on MicroVAX workstations with Ramtec high-resolution graphics systems. Operation during a run is more manual than automated, in that human players constantly interact with the system, directing the two sets of opposing forces. The system provides a menu interface for action choices, performs line-of-sight and movement calculations for each simulation entity (tank, APC, helicopter, etc.), and maintains detailed datasets of sensing and weapon effects. Special utilities allow the user to review and change terrain, alter scenarios, select new symbology, and adjust probability of hit and kill data.

The advantages of using JANUS are its speed and detail. It is able to rapidly simulate the behaviors of several hundred objects because it is programmed in a procedural language, FORTRAN, instead of Lisp or Prolog. Also, a lot of work has gone into its sensing and Pk mechanisms, making it accepted by some analysts for analysis of new tactics and systems. Its main limitations are in the difficulty of changing its code, its lack of intervehicle coordination (communications, group tactics), and its inability to model automated onboard systems. Many problems have also surfaced with respect to the sensing algorithms when multiple targets or multiple sensors are used. Some of these problems have been solved through use of CAGIS, described below, and some are being remedied in new JANUS updates.

CAGIS

CAGIS is a few-on-few simulation model developed at RAND to augment analyses performed with JANUS. It is programmed in C and acts in something of a "snapshot" mode, ex-

amining movement, sensing, and firing events in great detail. It has been used for exploring ground-based sensing algorithms in the antiarmor project, armor and helicopter engagements in an LHX evaluation study, and close air support operations for the Air Force.

CAGIS models terrain in much the same manner as JANUS and RISE, but has many augmentations to the sensor and mobility equations. The most important changes are that CAGIS can differentiate detection, recognition, and identification; it uses a multiple contact algorithm to establish acquisition; and it models the synergistic effects of multiple sensors on the same platform. Recently, CAGIS has been interfaced with several high-fidelity aircraft maneuver models—Champ (helicopters) and Blue Max II (fixed-wing aircraft), and with the the RJARS (RAND Jamming and Radar Simulation) System. CAGIS results from coordinated use of these algorithms will be fed into a corresponding JANUS simulation.

RISE

The RAND Integrated Simulation Environment (RISE) is also a detailed vehicle-on-vehicle simulation using high-resolution terrain modeling. While not as mature as JANUS, it offers a flexible and interactive environment for exploring ground vehicle concepts. RISE is written in Lisp and is object-oriented in form. Each object (tank, helicopter, road, bridge, etc.) has its own database and behaviors, and actions are triggered in response to messages passed between objects. This organizational structure is modular and transparent, and is becoming a standard in advanced simulation. RISE also supports rule-based behaviors by interacting with expert system shells. The RISE environment, composed of RLISP, INGRESS database management system, and GKS graphic interface, is similar to some of the multipurpose expert system tools now being marketed, such as KEE, Knowledge Craft, and Loops, but it is specifically oriented toward AI-based simulation. The system graphics are somewhat limited compared to high-fidelity simulators (especially those with three-dimensional videodisk and computer-generated imagery systems), but the RISE GKS system will generate a reasonable array of graphic views, including map, status, and sensor displays.

The terrain representation in RISE provides a background upon which the engagement is played. We are currently using 6 km × 6 km and 20 km × 20 km areas derived from DMA databases, with 50 meter grid size. Each 50 meter point has information about elevation, cover, and special features such as roads, rivers, and buildings. Many of the features are coded as objects (e.g., roads have throughput, load, etc.) and are stored in and accessed from a separate database. The terrain and feature information is used to calculate intervisibility, mobility, and weapon effects.

The RISE-based RCV simulation is at a preliminary implementation stage, with background terrain, object movement and engagement, line-of-sight calculations, and some AI-based reasoning in the RCV modules. Behaviors include communications, route search, deployment planning, tactics inference, and engagement behaviors (including coordinated actions). The system consists of multiple Sun and HP workstations.

The advantages of the RISE system are its interactivity, its ability to model on-board AI modules, and its ability to simulate cooperative behavior among units. Its disadvantages are speed (mainly due to Lisp) and its limited library of detailed sensing and Pk routines. RISE has been useful primarily for examining architectures and implementations for the various AI modules, estimating processing and memory support requirements, and passing parame-

ters to a more detailed simulation such as JANUS. Plans are under way to integrate RISE and JANUS.

CASTFOREM

CASTFOREM (Combined Arms and Support Task Force Evaluation Model) is an old member of the Army Hierarchy of Models. Like JANUS, it runs at battalion/brigade level with resolution down to platoons and individual weapons. It was supposed to feed into a corps/division model (now VIC) and then to FORCEM. CASTFOREM is written in Simscript II.5 and typically runs in a ponderous batch mode on a VAX 780. The human does not normally interact with the simulation during a session, but can stop it and change parameters. Not all actions are scripted, as there are decision tables for responses. Most outcomes are stochastic.

Terrain in CASTFOREM is taken from DMA data and represented as hex areas. This reduces the effectiveness of the model for sensor, communication, and weapons effectiveness calculations. It does have limited models of weather, battlefield obscurants, NBC, and electronic warfare. It does not have graphics output.

A similar battalion-level model is BLDM, the Battalion Level Differential Model, by Vector Research. It is deterministic, but it does have detailed terrain (from the NATO Reference Mobility Model used at TACOM). It uses a maneuver preprocessor to perform mobility calculations. Programmed in FORTRAN, it provides detailed vehicle resolution outcome information—munitions used, firing events, kills, and so forth. There are some automated algorithms for target acquisition and target allocation behaviors, but communication is not modeled and no graphics are present. The only advantage over JANUS seems to be in some of the automated behaviors.

Carmonette

Carmonette is another old Army model. It is at the same level as CASTFOREM and JANUS, but is a batch FORTRAN model without graphics. Up to 500 maneuver units per side can be supported, with digitized terrain up to 10 km × 15 km. Most entries are in the form of movement paths and scripts, with mobility treated as a speed degradation according to the type of terrain. No changes can be made during a game. Two terrain areas are used—Fulda Gap and a region in the Middle East—but there is no cover detail. No decision tables are used. Outcomes are determined probabilistically in terms of catastrophic kills. Like CASTFOREM, there is no graphics output. The system is supposed to be used to analyze battalion-level combat doctrine and tactics.

VIC

The Vector in Commander (VIC) combat simulation is a high-level, two-sided, deterministic model of corps-level command and control. RAND has been running the system for the

past year with scenarios from the Fulda area. The simulation is said to be rather cumbersome. It requires weeks of manual input, and the system runs in a batch mode with huge amounts of output. A typical two-day (40-hour machine time) run of a SCORES scenario will produce 200 Mbytes of output. RAND staff members have transferred the system to a Sun environment. The system typically goes down to the battalion level. It is one of the few simulations that model detailed logistics operations.

Postprocessing uses FORTRAN routines. Some postprocessing graphics displays are being developed. The nice thing about VIC is its many components. It has coarse models for command and control, sensor collection, fusion processing, electronic warfare, maneuver unit combat, engineer operations, large area smoke, support fire, air operations, and combat service support. Unfortunately, it has very coarse terrain grid squares with gross trafficability, visibility, and weather effects. The model is designed to feed into FORCEM, a similarly large SIMSCRIPT program at the theater level.

Campaign 3.0

Campaign 3.0 is another higher-echelon simulation, modeling theater-level operations at brigade and division resolution (depending on the sides and force levels). The system is used for the Force module of RSAS (the RAND Strategy Assessment System) and for a TACSAGE/TASK/CAMPAIGN combination of models. It dos not have a detailed terrain model, but uses some 500 "zones," consisting of squares along ten axes across Europe. Time increments are four hours, and outcome adjudication is by Lanchester equations or special inputs from the user All major elements are modeled—tank, mechanized infantry, artillery, air defense, helicopters, etc. The system runs in an automated mode once all the inputs are set, but the user can choose to run it for a set number of days and change conditions. Some command and control coordination is modeled between army groups, corps, and divisions. The system is programmed in C on a Sun 3 with 8–12 Mbytes of memory. It takes several months to properly set up a plan, but only 10–20 minutes to run a 20-day war.

Secondary Land Theater Model (S-Land)

S-Land is a new battalion/division-level model used for simulating theater combat in RSAS. It uses more fully the rule-based modeling and decision-table capabilities of RAND-ABEL (a language on top of C) than does Campaign. Model subcomponents perform the piston-like attrition and forward edge of the battle area (FEBA) movement calculations using Lanchester equations, but the emphasis is on military operational concepts. The model differentiates between such aspects as battles in narrow mountain passes and pursuit phases subsequent to a breakthrough. Campaign models such phases to a lesser extent.

Initial applications of the system have been to theaters such as Norway and Turkey. The modeling is done at high level, with emphasis on battle zones. The design is supposed to be well suited for division- and corps-level modeling, although this would take some time for modification. The system should be very fast and transparent.

T-SAGE

This is another high-level FORTRAN batch model at RAND. It simulates the engagement of some 100 Red divisions against 60 Blue ones. Resolution is down to regiments or brigades. T-SAGE has homogeneous cells or grid squares, and uses Lanchester equations for outcome calculation (losses and FEBA movement). All activities (communications delays, movement, jamming, smoke, etc.) are assumed to be implicit in the outcome calculations. No manual inputs are permitted during a run. The only graphics are in the off-line analysis programs. A run takes about eight hours on a Sun 3/260.

ConMod

ConMod is essentially a high-level, automated extension of JANUS. It is programmed in ADA rather than FORTRAN, but uses the same graphics package as JANUS (Tectronics high-resolution graphics engines). Unlike JANUS, inputs are made through MAC-type windows rather than simple menus. This model operates at the echelons-above-corps level.

ConMod is supposed to have several key automated planning algorithms, each of which can call the others:

- Pathfinder is a search algorithm similar to our route planner in RISE. It is based on the A* algorithm and is supposed to be used for some 25 different planning operations—finding on-road and off-road routes, bottlenecks, corridors, etc. It has been demonstrated at both the high level (corps, division) and at the low level (platoon).

- Middle-level operational planning. This module, called the cooperative coordinating parallel planner, takes a high-level goal and set of constraints and attempts to generate coordinated plans to accomplish the goal. It takes into account limited resources, terrain, command hierarchy, and time. The module generates plans over several passes until an acceptable plan is found.

- Strategy finder is the highest-level module, taking global goals and using engagement simulation to decide on strategy. It takes into account enemy strength and reactions.

To accomplish the above functions, ConMod will eventually have search routines, scripts, object-oriented structure, an expert system shell, and even a neural network. The neural network is supposed to make a fuzzy pattern match on strategies, observe the losses or FEBA movement, and adjust planning parameters accordingly.

The system is programmed in ADA, except for some FORTRAN graphics routines. It should be fast (less than 1 second for path finding, a few minutes for strategy finding). It runs on a set of VAXen. The system should be able to perform automated planning at all levels from EAC down to JANUS objects. A proof of principle (databases, planners, communication) system was demonstrated in 1988. The system did not have a human interface, and the prototype system will not have interrupt capability.

SIMULATORS

As noted before, simulators differ from simulations in that they attempt to inject apparent contextual realism into the man-machine interaction. They use high-fidelity mock-ups of the crew stations; they sometimes introduce vehicle sounds and vibrations; and they typically use computer-generated imagery or videodisk-produced scenes to drive the display screens and respond to control inputs.

We have examined several candidate simulators, among them the Honeywell Crew Display Demonstrator, the Perceptronics/BBN SIMNET and SIMCAT systems, the GD Land Systems three-man crew demonstrator, the RCA Universal Crew Station, the Delco Tank Turret Simulator, the European APKA II and III simulators, and the General Electric UCOFT Trainer. These computer-based systems range from individual station trainers to large-scale battle simulators. In our examinations below, we will distinguish between systems for isolated crews and systems involving multivehicle coordination.

Our primary needs are realism and flexibility. The simulator should generate real-time sensor inputs to the operators, including simulated video, IR, MMW radar, and laser rangefinding and scanning. It should include all crew functions (navigation, targeting, communication, etc.) with all associated displays at each crew station. It should be able to run through a variety of combat scenarios, provide realistic dynamics, and maintain performance histories. It should in some fashion accommodate our AI modules, and it should allow comparison of two-man concepts with more conventional three- or four-man crew designs.

Honeywell VCDD

The Honeywell Vehicle Crew Display Demonstrator (VCDD) is a system developed under the Army Vetronics program. It is intended to be a general testbed for evaluating different crew station configurations for armored vehicles. Displays include low-light-level video and FLIR inputs, horizontal map display, vehicle status graphics, vehicle control graphics, and textual recommendations. There are multiple high-resolution display screens, programmable touchpads, control sticks, and T-bars. The system is run by a VAX 11/785 and four Silicon Graphics drivers, and two Trillium computer-generated imagery (CGI) systems. One to three stations are managed from a controller station with repeater displays. Initial demonstration of the system took place in early 1987.

The Honeywell VCDD environment, while limited to control and display configurations, is quite extensive and realistic. Honeywell has contracted for CGI with perspective and real-time pan and zoom. The system can show overlays and text, and allow graphic inputs for object or location designation. Honeywell is also planning to add extensive performance monitoring—situation assessment accuracy, hits, losses, communication load, and the like.

The scenarios used in the VCDD seem to be at an appropriate level. There are supposed to be platoon-level missions of hasty attack, movement to contact, and hasty defense. They can have up to 20 enemy objects (T-72s, helicopters, AA), each of which has preprogrammed responses to the friendly objects. Terrain is well represented, with line-of-sight calculations and exposure measurements. The vehicles do not have to follow straightline paths from node to node, moving instead over a continuous terrain. Enemy objects are similarly maneuverable, using either automated navigation or manual control.

Communications in the VCDD are by voice, digital, or graphic. The controller can role-play with voice or can record and activate digital messages. The operators can send messages in voice or digital modes. There is no capability as yet to degrade the messages (noise, delays, jamming), but this should not be difficult. All actions are manual.

The two forms of sensing now planned for the VCDD are low-light TV and FLIR. The graphics displays showing these signals are supported by CGI databases, and include different sun angles and night engagements. Other forms of sensing (MMW radar, laser scanning, laser designation) might be simulated by degrading or changing the databases, although shape and vibration information normally provided by laser scanning may be difficult to obtain in this way. There are plans for uncertainty representation and display of confidence estimates on the graphic displays. An important feature is that displays at different crew stations can be driven independently, which should facilitate simulation and comparison of two-, three-, or four-man systems.

The VCDD system is designed primarily for single-crew operation. Minimal intervehicle crew interaction is possible. One role for the VCDD would be to develop and integrate the RCV AI modules under realistic display and control imagery. In conjunction with analyses using the JANUS system, this system should allow us to develop a first-level integration of the RCV modules. It should allow us to perform human factors analyses with different control/display interfaces.

Perceptronics/BBN SIMNET System

The Perceptronics/BBN SIMNET system is a much larger and more ambitious simulation system than the VCDD. It nets together groups of high-fidelity tank crew simulators, allowing detailed studies of tactics and doctrine. A training version (SIMNET/T) was demonstrated in late 1986, and many sets are now in operation in the United States and Europe. Networks of ground vehicles (M1s and M2/3s), air defense units, helicopters, and A-10s have been demonstrated at Fort Knox. The air vehicles are configured by taking the eight channels from the tank's Delta graphics CGI system and routing them to CRTs placed on the cockpit mock-up's windscreen. Each CRT represents an 8 × 20 deg view refreshed at 15 Hz. A special FLIR image is included with the helicopter unit. The SIMNET/T system is said to be very successful. Some 240 ground and air units will be completed on the current contract.

A concept development (SIMNET-CD) version has also been prepared. This CD system is the focus of our interest. BBN is the prime contractor, and they claim that it is much more flexible and reconfigurable than the training version. A few SIMNET-CD units are in operation at Fort Knox, in a building next door to the SIMNET/T facility.

The SIMNET-CD system should offer a fairly complete development environment for exploring, developing, and testing the RCV system. Like the T system, each CD node provides a simulated environment for an entire tank crew, including visual, auditory, and tactical stimuli. The nodes are networked and crews engage each other, resulting in movement, resource depletions, damage, kills, and most of the other outcomes of combat. All of the stations are manned in the SIMNET/T training version, but the SIMNET-CD version has some automated functions and should be highly reconfigurable. Some of the additions to the T system are a position navigation system and the Intervehicular Information System (IVIS).

This system shows tactical information on a map display, and sends digital communications through a simulated SINCGARS channel to other vehicles.

Several functions can be implemented with the SIMNET system that would not be possible with our in-house simulations or the VCDD simulator. These include an adaptive man-machine interface, an interactive analysis capability, and a maintenance and supply status module. The man-machine interface may include both the traditional display/control design process and a specification of an adaptive "division of responsibility" between the operators and the computer system. The system will observe the operator activities and the situation conditions present and adjust its functions and displays accordingly, presenting only that information important to the operator's functions and taking over other, lower-priority functions entirely. In this mixed initiative fashion, it will also aid in such traditional MMI functions as screen pan, zoom, highlighting, alerting, and decluttering. The second function, interactive analysis, is achieved through use of a special monitor that acts as a "stealth jeep," allowing the user to nonintrusively move through a real-time scenario, observing engagements, maneuvers, and losses as they occur. The capability is augmented by special postprocessing tools. The last function, maintenance and supply status, will be an expert system for tracing system faults, checking system functionality, and reconfiguring subsystems in the event of failure. It will also recommend actions for the crew to undertake, such as calling backup vehicles for maintenance, supply, and repair operations (which are simulated using special manned terminals). All of these expert systems applications can be programmed in Lisp or C and interfaced to the SIMNET databases.

SIMNET has recently been updated by BBN to SIMNET-II, a version with three times the graphics speed and image resolution. This performance improvement was found to be especially important for helicopter and air defense displays. In the future, some 1500 stations will be produced under the CCTT (Close Combat Tactical Trainer) program.

APKA II and III

APKA is another complex simulator system. Unlike the VCDD, SIMNET, and the other simulators, the operators do not get a perspective, soldier's-eye view. The system is primarily for command and control training, and each operator is given a bird's-eye view of the situation in the form of a horizontal map display with overlays of those vehicles in LOS. The phase II system is called TACMASS and is used by the U.S. Corps in Freiburg. It models tanks, APCs, helicopters, artillery, and air defense units. A big advantage is its detail. Its terrain maps are at 6-meter horizontal and 2-cm vertical resolution. It can model a wide range of weapons, including electromagnetic gun and HVM, and a wide range of sensors, such as MMW radar and laser radar, all by updating table parameters. There are 18 stations with three operators each that may be configured in a nine-on-nine engagement, or all 18 may be Blue against an automated Red force. Each station may also represent a platoon, company, or higher-level unit. Communications between units are supported.

The European version, APKA III, is supposed to have more stations and more flexibility than TACMASS. A combination of SIMNET and TACMASS or APKA III for tank and unit commanders may be effective.

Singer Link-Miles/GE COFT

Another high-fidelity tank gunnery trainer is the Singer Link-Miles Conduct of Fire Trainer (COFT). A similar version is the GE Integrated Conduct of Fire Trainer (ICOFT) at Fort Knox. It is a large trailer unit with an accurate reproduction of a tank turret, with seats for gunner and commander. It has realistic sounds and full color visual imagery. Unlike SIMNET, however, units are not interconnected, and there are no plans for a concept development system. The system seems useful only for training. It does have high-resolution graphics and impressive detail such as coax firing against infantry and light vehicles.

RCA Universal Crew Station

The Universal Crew Station (UCS) is a two-man crew demonstrator built under the Vetronics Phase I competition. The UCS has day color TV cameras providing the input images, with a scene of the New Hampshire countryside overlaid with simulated Russian tanks. There is also a map display with C^3I overlays, and a diagnostic display that goes down to the board level. High-speed and 1553B bus networks transmit the data between several electronic units and to the color CRTs for the two side-by-side operators. There are no flat panel displays. In one way or another, they can simulate many of the key characteristics of an engagement—sensing, laser ranging, moving, fire control, etc. The views are essentially those of the commander's sight and the CITV.

Delco Tank Turret Simulator

This is a recent system, completely Delco funded, that was used to explore new tank crew station designs. It is a mock-up of a tank turret, originally planned as a manned weapons station replacement for the M1 turret. It has a German 120-mm autoloader on the left and a fore-and-aft two-man crew station on the right. Sensor input is from a CCD day TV camera mounted on the 40-ft-high building roof. The signal is routed down a fiber optic video link to color CRTs and monochrome flat panel displays (8 × 8 in. plasma). The operators have standard M1 yoke controls along with British Chieftain hand sticks. The flat panel displays have touch screens much like the GD Land Systems IVIS demonstrator. The Delco human factors group tried showing pages of automotive, diagnostic, and map information on the flat panel displays. They also explored concepts for a soldier-machine interface (SMI) by producing some 93 computer-generated pictures, displayed on the 8 × 8 in. flat panel display. These represented each display/control event for a portion of a "delay in sector" defensive operation. They assumed a thermal viewer (such as the CITV) and MMW radar.

The system seems suited to only a part of our work, but there were some interesting findings on fiber optics links. A noncoherent fiber optic slip ring unit was a concentric set of two 8-in. diameter washers. The video signals from two TVs were modulated into two colors and transmitted between the washers, with only minor loss of fidelity.

GD Land Systems Three-Man Crew Demonstrator

The GDLS Three-Man Crew Demonstrator is a large piece of equipment that mocks up the interior of a fairly conventional tank, except it has three side-by-side crew stations. The simulation was internally funded, and a version is operational at Fort Worth. Unfortunately, the system has only conventional displays and controls. All stations have periscope-type viewing, and the controls are a driver's yoke, a gunner's yoke, and (the only interesting aspect) a commander's set of side sticks. The scenario and imagery are taken from a prototype GDLS COFT system. The main interest of the system is that the human factors group is planning to interface and test their IHADDS helmet-mounted display with it.

CONCLUSIONS

The best simulations for armor/antiarmor analyses appear to be Ground Wars for weapons effect modeling, JANUS/CAGIS for small-unit tactics analysis, RISE for in-house exploratory studies of AI modules and individual crew operations, and Campaign/S-Land for high-level, coordinated operational maneuvers. For simulators, the VCDD and SIMNET/CD systems provide suitable environments for single-vehicle and multivehicle explorations. Unfortunately, the simulator group seems to be largely in hiatus now, awaiting the next round of Vetronics contracts. Once new funding is given, the RCA and Delco systems may be good testbeds. Meanwhile, SIMNET is fast becoming an Army standard for training and analysis, and appears to have the most promise for continued work.

BIBLIOGRAPHY

Aviation Week and Space Technology, "Revolution in the Cockpit," April 11, 1988, pp. 59–75.

Bolte, Philip L., "Vetronics: What It's All About," *International Defense Review,* Armour Supplement, Vol. 7, 1987, pp. 13–17.

Calhoun, G. L., "Control Logic Design Criteria for Multifunction Switching Devices," *Proceedings of the 22nd Human Factors Society Meeting,* 1980.

Chrysler Defense, Inc., *Characteristics and Description Book, M1E1 Tank,* Report TA-80-01105-002, October 1981, pp. 2–16.

Demers, W. A., "Services Eye New Visual Systems," *Military Forum,* March 1988, pp. 19–21.

Earl, W. K., *Human Factors Engineering Design Criteria for Future Systems,* ARI, Report ARI-RP-84-05, March 1984.

Earl, W. K, *Human Factors Evaluation of the M1 Combat Tank in Operational Test III,* ARI, Report ARI-RR-388, December 1984.

Ebate, Kensuke, "Japan's New TK-X Main Battle Tank: Initial Impressions," *International Defense Review,* No. 6, 1988, pp. 655–658.

Fletcher, Robin, "Main Battle Tank Crew Reduction," *International Defense Review,* Vol. 1, 1987, pp. 69–73.

Fletcher, Robin, "Tank Guns Against the Attack Helicopter," *International Defense Review,* No. 6, 1988, pp. 637–640.

Geysenheyner, Stefan, "Radar and Laser Warning Receivers," *Military Technology,* February 1986, pp. 36–43.

Harper, G. M., and J. R. Underwood, *Final Electric Drive Study Technology Survey Report,* General Dynamics Land Systems, Report JU-84-04057-001, January 1985, pp. 4.1–4.12.

Hewish, Mark, Gerard Turbe, and Paul Turk, "Tank Fire-Control Systems," *International Defense Review,* No. 6, 1988, pp. 765–777.

Hilmes, Rolf, "Battle Tank Mobility," *International Defense Review,* Battle Tank Supplement, Vol. 9, 1985.

Howard, Cheryl, and Dennis Van Derlaske, "Standardized Advanced Infrared Sensor: A Program Status," presented at 1988 Helicopter Society Meeting.

Hughes, David, Bell Labs Report Breakthrough in Gallium Arsenide Detectors, *Aviation Week and Space Technology,* September 5, 1988, pp. 205.

Jane's Avionics, "Electro-Optics," Jane's Publishing, New York, 1987–1988.

Jane's Avionics, "Lantirn low-altitude navigation and targeting infra-red system," Jane's Publishing, New York, 1985.

Jane's Military Communications, "Joint Tactical Information Distribution System (JTIDS)," Jane's Publishing, New York, 1987.

Jane's Weapon Systems, "Spasyn Visual Target Acquisition System," Jane's Publishing, New York, 1987.

Johnson, Philip, "Tank Vision Systems of the Future," *Military Technology,* No. 6, 1984, pp. 55–56.

Kales, David, and Albert Tebo, "Markets and Technologies for Detectors Expand in 1987," *Laser Focus/Electro-Optics*, December 1987, pp. 89–98.

Kandebo, Stanley, "Navy to Evaluate Agile Eye Helmet-Mounted Display System," *Aviation Week and Space Technology*, August 15, 1988, pp. 94–99.

Kaplan, Herbert, "Photonics at Work: Long-Wavelength IR Fiber Optics," *Photonics Spectra*, April 1988, pp. 82–84.

Kelly, Donald W., and Mark C. Spear, "Lantirn: A Technica Report," *Defense Electronics*, September 1986, pp. 63–68.

Kelly, James H., *Gun Propulsion: Emerging Army Technologies*, Jet Propulsion Laboratory, JPL Report D-3294, August 1986.

Klass, Philip J., "European Firms Increase Efforts to Develop Millimeter Wave Radars," *Aviation Week and Space Technology*, September 5, 1988, pp. 153–155.

Lenaerts, Jacques, "Design Criteria for AIFV Turrets," *Military Technology*, No. 3, 1988, pp. 16–24.

Melendez, E. M., and H. L. Resnick, "Vetronics Drives Vehicle Development," *Defense Electronics*, October 1986, pp. 123–137.

Pengelley, Rupert, "Putting Steel on the Target: U.S. Tank Fire Control," *International Defense Review*, No. 12, 1986, pp. 1823–1829.

Pengelley, Rupert, "AFV Propulsion: Americans Advocate Integration," *International Defense Review*, Vol. 5, 1988, p. 542.

"Research and Technology: Section, Laser Radar," *International Defense Review*, No. 6, 1988, pp. 719.

Robinson, Christopher, and Ray Eberts, "Comparison of Speech and Pictorial Displays in a Cockpit Environment," *Human Factors*, 1987, Vol. 29, No. 1, pp. 31–44.

Shultz, James B., "Ruggedized Computers Offer Low-Cost Readiness," *Defense Electronics*, January 1987, pp. 69–79.

Simpkin, R. E., *Human Factors in Mechanized Warfare*, Brassey's, New York, 1984.

Sweetman, Bill, "Challenges for the One-man Cockpit in the ATF," *International Defense Review*, No. 5, 1985, pp. 687–689.

Sweetman, Bill, "Combat Cockpit of the Future," *International Defense Review*, No. 4, 1988, pp. 363–366.

Tillen, Ron, "A U.S. View of the Markets for Military Electro-Optics," *Special Electronics*, No. 3, 1984, pp. 9–24.

Turbe, Gerard, "Leclerc: A Third-Generation Battle Tank," *International Defense Review*, Vol. 6, 1987, pp. 755–760.

U.S. Army TACOM, *M1A1 Tank System Weights*, Report AMCPM-CGM-SA, May 1987.